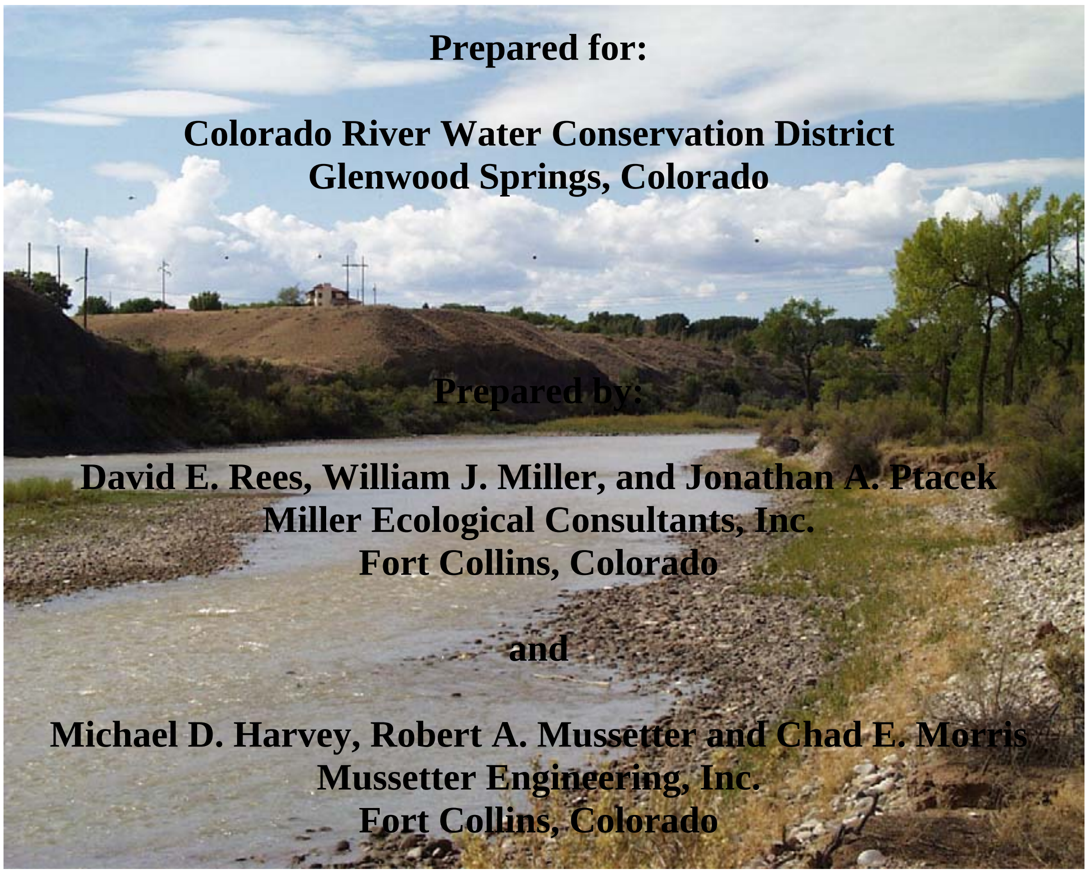
Volume 1
Draft Final Report

Ecological and Physical Processes during Spring Peak Flow and Summer Base Flows in the Colorado River



Prepared for:

Colorado River Water Conservation District
Glenwood Springs, Colorado

Prepared by:

David E. Rees, William J. Miller, and Jonathan A. Ptacek
Miller Ecological Consultants, Inc.
Fort Collins, Colorado

and

Michael D. Harvey, Robert A. Mussetter and Chad E. Morris
Mussetter Engineering, Inc.
Fort Collins, Colorado

March 30, 2004

MILLER ECOLOGICAL CONSULTANTS, INC.

Executive Summary

Background

The 15-Mile Reach (15-MR) of the Colorado River is located between the Gunnison River confluence at Grand Junction (River Kilometer (rkm) 275.1) and Palisade (rkm 298.1), Colorado (Figure ES-1). Populations of federally-listed threatened and endangered native fish species (Colorado pikeminnow, *Ptychocheilus lucius*, and razorback sucker, *Xyrauchen texanus*) occupy this reach of the river, and it has been suggested that their recovery is dependant, among other factors, on increasing depleted spring snowmelt runoff peaks (Osmundson, 1999). It has been hypothesized that increased peak flows are required for channel maintenance purposes and for removal (flushing) of fine sediment from gravels and cobbles that constitute the bed material of the river (Osmundson et al. 1995). It has also been suggested that removal of fines from the bed of the river as a result of bed mobilization by increased peak flows would increase periphyton and macroinvertebrate productivity, and thus increase the overall carrying capacity for the listed fishes of the Upper Colorado River (Lamarra 1999; Osmundson and Scheer 1998; Osmundson 2002). A number of previous studies on primarily salmon spawning streams and rivers have shown that fine sediment cannot be winnowed or flushed from appreciable depths without mobilization of framework gravels (Diplas 1994; Wilcock et al. 1995; Kondolf and Wilcock 1996; Milhous, 1999).

Historic suspended sediment loads in the Colorado River were probably higher prior to 1940, primarily as a result of widespread arroyo incision that commenced in the mid 1800's (Thompsen, 1982, 1984; Gellis et al, 1991). Even though the sediment concentrations have remained relatively constant in the last 50 years, total sediment loads in the 15-MR have been reduced because of the reduced flows (Pitlick and Van Steeter, 1998). Since the 1950's there has been a 30 to 40 percent reduction in the magnitudes of the 2- and 5-year peak flows as a result of upstream water development projects (Pitlick et al. 1999; this study). Reductions of the peak flow magnitudes and reduced suspended sediment loads have caused a 10-15 percent reduction in average channel width, and about a 25 percent reduction in side channels and backwaters (Van Steeter and Pitlick, 1998; Pitlick and Van Steeter, 1994; Pitlick et al, 1999). Regardless of the changes in hydrology and sediment supply, Pitlick et al. (1999) concluded that the current channel morphology in the 15-MR is in equilibrium with the current peak flow regime and suspended sediment load, and therefore, it can be concluded that there are unlikely to be further channel adjustments if the present peak flow regime is maintained.

While the current morphology of the Colorado River within the 15-MR may be in equilibrium with the post-1950's peak flow regime, the question of the adequacy of the current peak flow regime for fine sediment flushing and biological productivity (Osmundson et al, 2002) cannot be addressed by a generalized study of sediment mobilization. Pitlick et al (1999) identified discharges for incipient mobilization of the bed material (10,000 cfs) and for general mobilization of the bed material (22,000 cfs), but as pointed out by Downes et al (1997) flow-sediment-habitat relations occur at micro-and meso-scales levels that are not represented by macro-scale analyses.

The initial focus of this study within the 15-MR was to address the hypothesis that the current peak flow regime is limiting to the recovery of the listed native fish species and the aquatic

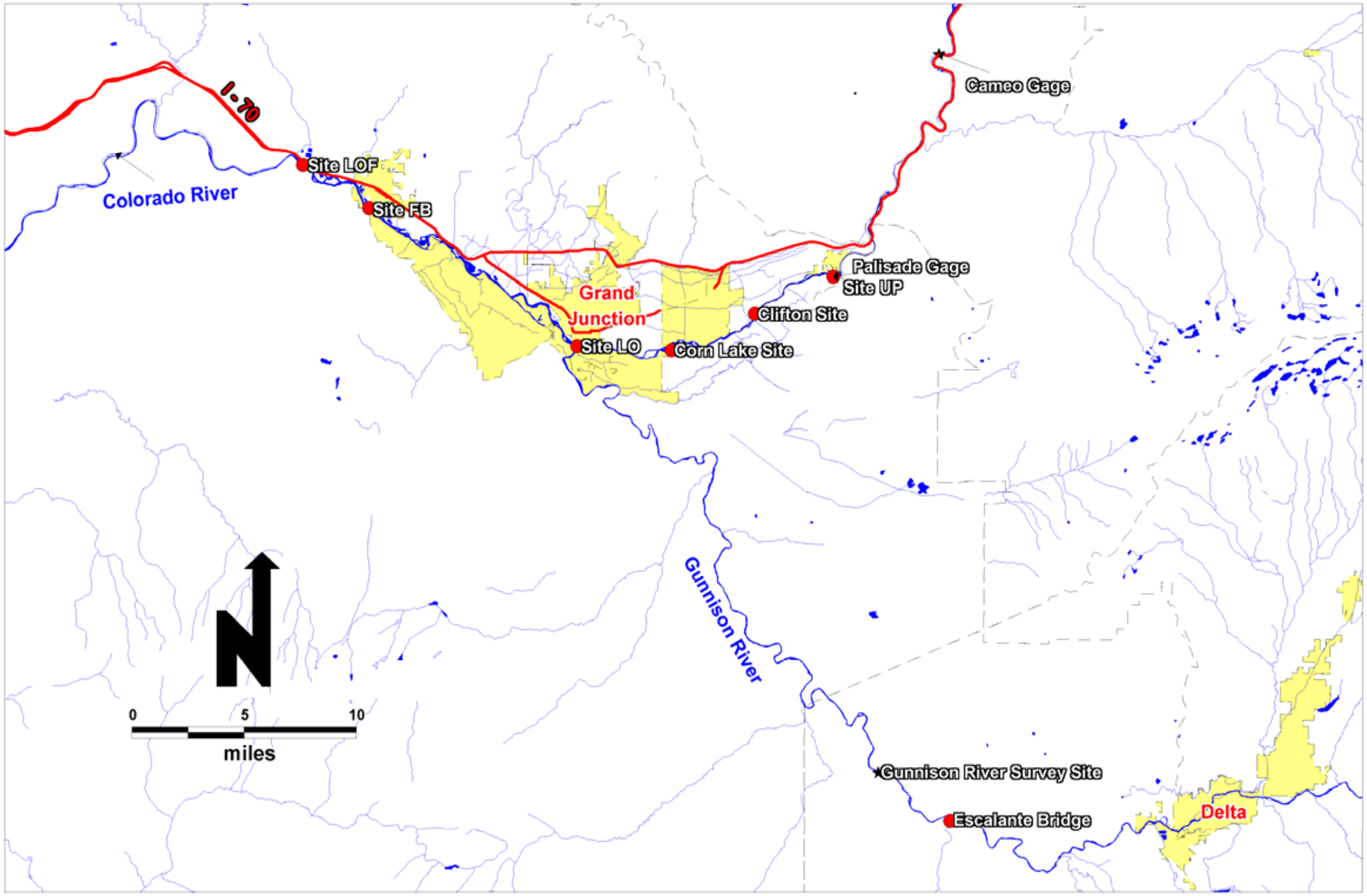


Figure ES-1. Map showing the locations of the Colorado and Gunnison Rivers and the locations of the MEC/MEI data collection and analysis sites on both rivers. Also shown are the locations of the Cameo and Palisade gages.

community on which they depend. To understand the interactions between flows, sediment delivery and biological productivity in the 15MR of the Colorado River, a series of physical and biological investigations were made over a five-year period at the Clifton study site.

Physical Process Investigations

The primary goals of the physical process portion of this investigation were to address specific aspects of the sediment dynamics of the 15-MR at meso- and micro-scale levels so that they could be directly related to the quality of the habitat in the riffles and runs, and hence biological productivity. These investigations focused on the role of peak flows and baseflows on bed material mobilization and deposition, and removal of fine sediment (mud) from gravel and cobbles within the various geomorphic subunits (riffles and runs) that are present in the 15-MR.

The specific areas of investigation and the findings of this study were as follows:

- Factors that control the supply of fine sediment to the 15-MR and the timing of the sediment supply.

  The fine sediment is derived from the lower elevations of the UCR basin that are underlain by highly erodible sedimentary rocks. The fine sediment, that is composed mainly of fine sands, silts and clays, is delivered to the Colorado River during baseflow periods primarily by summer thunderstorms that do not increase the discharge of the Colorado River greatly, but do increase the suspended sediment concentrations. Even though suspended sediment concentrations have not changed appreciably in the last 50 years, they are lower currently than they were prior to the 1940's.

- The hydrodynamic conditions within the reach that permit mud deposition and the resulting spatial distribution of the mud within the reach.

  Velocity and shear stress thresholds for fine sediment (mud) deposition and erosion were identified from field measurements at the Clifton and Corn Lake sites. At locations where velocity and shear stress are higher than 2.5 fps and 0.03 lb/ft^2, respectively, mud is not deposited in appreciable quantities. The good correlation of the mapped boundaries of the mud mapping units with the predicted boundaries from 2-D modeling at Clifton enables the spatial distribution of the mud at the site to be predicted with reasonable precision over a wide range of flows.

- The hydrodynamic conditions within the reach that permit general mobilization of the gravel and cobble that constitute the bed sediment in the riffles and the runs.

  Incipient motion calculations based on output from the 2-D model of the Clifton site identified critical discharges for the riffles and the runs. The critical discharge in the riffles is about 4,800 cfs, and in the run it is between 13,000 and 15,000 cfs. General mobilization of the bed material throughout the site occurs at flows in excess of 20,000 cfs.

- The range of flows required to deposit and remove fine sediment from the bed of the channel.

  Provided that fine sediment producing events have occurred in the upstream tributaries, fine sediment (mud) is deposited at various locations within the Clifton site where the velocity is less than 2.5 fps or shear stress is less than 0.03 lb/ft^2. Mud is re-entrained from these locations when the identified velocities of shear stress thresholds are exceeded. The results of the 2-D modeling of the Clifton site indicate that at a flow of 800 cfs (equaled or exceeded 92 percent of the time), about 35 percent of the site is relatively mud-free. At flows of 1,100 cfs and 1,400 cfs (equaled or exceeded about 80 percent of the time), about 47 to 54 percent of the site is relatively mud-free. At a flow of 2,000 cfs (equaled or exceeded 45 percent of the time), about 67 percent of the site is mud-free. About 85 percent of the site is mud-free at a flow of 4,800 cfs (equaled or exceeded 16 percent of the time).

- Whether it is necessary to mobilize the underlying coarse-grained bed material for flushing of accumulated fine sediment.

  Flushing of fine sediments from the gravels and cobbles that make up the bed of the river in the riffles and runs at the Clifton site occurs at flows in excess of 4,800 cfs and 13-15,000 cfs in the riffles and runs, respectively, when the critical discharge is exceeded, and this is described by the framework response of the process-response model. However, the results of the 2-D modeling show that the surficial fine sediments can be re-mobilized and flushed by less than the critical flows for the underlying bed material throughout the Clifton site. This is described by the transient response portion of the process-response model.

Biological Investigations

The biological portion of this study was developed to provide specific and detailed information describing the relationship between physical processes (including peak flows) and periphyton and macroinvertebrate communities. This approach provided an opportunity to assess the influence of peak flows and other physical processes that may affect periphyton and macroinvertebrate communities during summer and fall seasons.

The objective for the biological investigations was to quantify primary and secondary production, and then determine if the present fish biomass appeared to be limited by the available productivity. Specific objectives and conclusions from the biological portion of this study are as follows:

- Are primary and secondary productivity and standing crop dependant on magnitude of peak flow?

  Magnitude of annual peak flow had little or no measurable effect on most of the variation observed in periphyton and macroinvertebrate communities in the 15-MR during this study.

- Is there a relationship between turbidity produced by summer thunderstorms and standing crop of macroinvertebrates and periphyton?

  There were significant relationships between levels of turbidity and all aspects of periphyton and macroinvertebrate community structure that were statistically analyzed.

- Is there a difference in primary and secondary production between two major habitat types (run and riffle) in the 15-Mile-Reach of the Colorado River?

  Periphyton and macroinvertebrate standing crop was much greater in habitats with higher current velocities. Aquatic communities in the 15-MR are dynamic and dependent on a variety of physical variables. Attributes of available habitat types result in differences in structure and function of the benthic communities that inhabit them. Evidence from five years of seasonal sampling suggests that periphyton and macroinvertebrate communities exhibit some predictable seasonal change, have specific habitat preferences or requirements, and are also dependant on physical processes. These results suggest that much of the biological variability can be attributed to physical processes that occur after snowmelt runoff.

Discussion

Physical Investigations

Water resource development projects in the Upper Colorado River basin upstream of the 15-MR commenced in the 1920's and by about 1950 approximately 45 percent of the annual streamflow was controlled (Pitlick et al., 1999). Suspended sediment concentrations at the UCR gages have not changed appreciably (Pitlick and Wilcock, 2001) as a result of the upstream dam construction in the last 50 years because of the high supply of sediment from the lower elevation portions of the basin that are underlain by highly erodible sedimentary rocks (Iorns, et al., 1965; Van Steeter and Pitlick, 1998; Liebermann et al., 1989; Spahr et al., 2000).

The Clifton Water Treatment Plant site (Clifton Site) was chosen as the location for micro-and meso-scale investigations after reconnaissance of the 15 MR in 1999. This site is representative of the 15 MR channel characteristics, is approximately 2,200 feet long with a mid-channel bar, large cross-channel riffles and cobble bars. A 2-D hydrodynamic model of the site was constructed from topographic and bathymetric data. The 2-D model output is better than a 1-D model at evaluating meso- and microscale habitat analyses of incipient motion and sediment transport (Mussetter et al., 2001).

Investigation of the relationships between flows, sediment loads and habitat requires that the temporal nature of the relationships be recognized and incorporated. In general terms, the annual hydrograph can be divided into low- and high-flow periods (Figure ES-2). The low-flow periods include late-summer and fall baseflows, as well as the winter baseflows that extend from about August to the end of April. The high-flow period includes the rising, peak, and falling limbs of the annual snowmelt hydrograph that usually extends from May to the end of July.

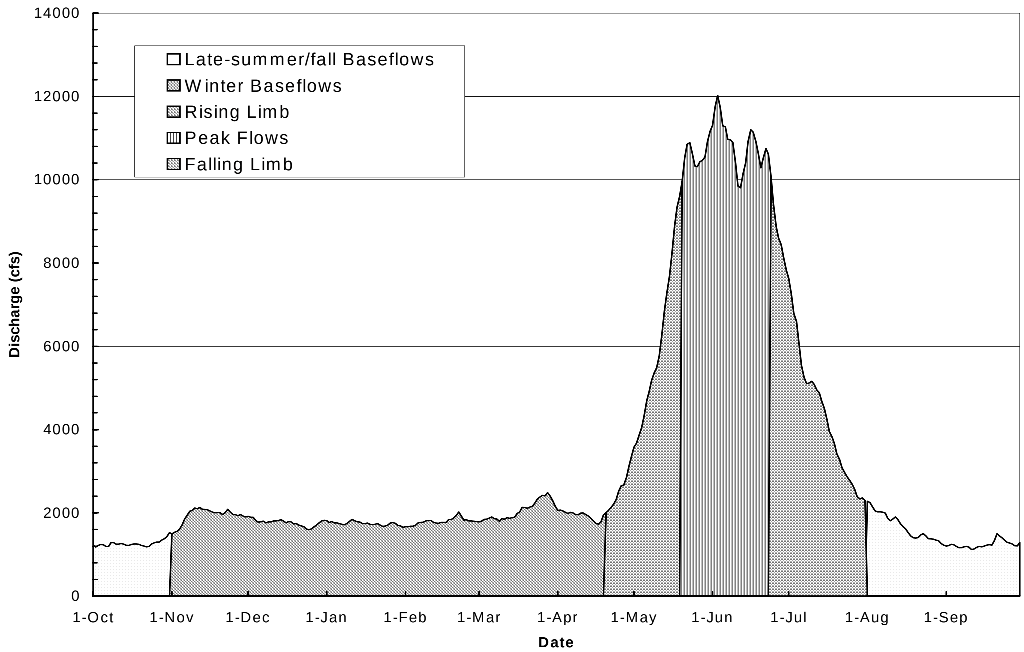


Figure ES-2. Mean annual hydrograph for the Colorado River at Palisade gage showing the subdivisions of the hydrograph discussed in the text.

The bulk of the annual sediment load is transported during the high-flow period when both the suspended load and bedload is transported (Pitlick et al. 1999) (Figure ES-3). The peak flows are, therefore, both morphologically and biologically important (Power, 2001). Pitlick et al. (1999) computed a reach-averaged critical discharge of about 10,000 cfs, and a discharge of about 22,000 cfs for general bed mobilization. Because of the effects of summer thunderstorms, suspended-sediment concentrations can be higher during the baseflow periods than peak flow periods. The quantity of sand, silt, and clay that is transported during the low-flow periods is relatively small, is dominated by silt and clays, and is morphologically unimportant but biologically very important. However, because of the stochastic nature of the thunderstorm events that generate the fine sediment, the sediments are not well represented in the USGS Cameo gage record that is based on fixed-interval sampling.

The physical system can be divided into two somewhat separate, but interconnected, response regimes, framework responses, and transient responses (Figure ES-4). Both have the ability to affect the biological productivity of the system by producing physical disturbances that affect both periphyton and macroinvertebrate trophic levels (Hildrew and Townsend 1987; Biggs et al., 1998). Framework responses are related to mobilization of the gravels and cobbles that form the bed of the river, and provide the habitat for the periphyton and macroinvertebrates (Biggs et al., 2001). In the context of the Clifton site, incipient conditions for the bed armor layer (D_{50} about 80 mm) occur at snowmelt runoff discharges that exceed approximately 4,800 cfs (less than a 1-year recurrence interval) in the riffles and about 13,000 cfs (about 1.6-year recurrence interval) in the runs. Mobilization and transport of the run and riffle sediments at discharges greater than 20,000 cfs (2.8-year recurrence interval) create a substantial disturbance to and reset of both the

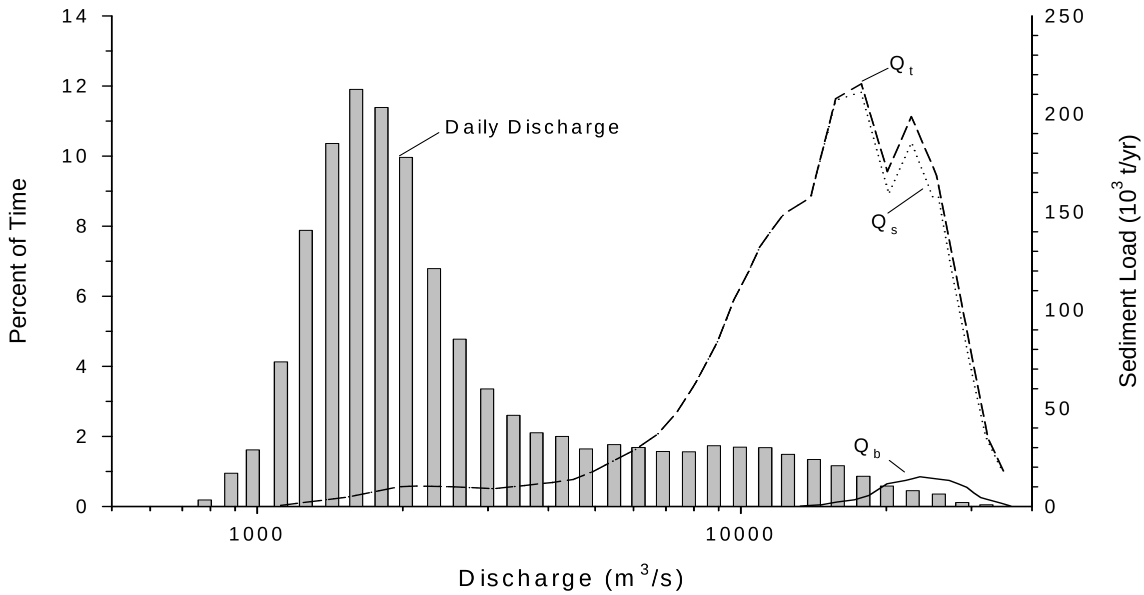


Figure ES-3. Summary of annual sediment loads at the Palisade gage. Q_t represents the total load, Q_s represents the suspended load, and Q_b represents the bedload (modified from Pitlick et al. 1999).

periphyton and macroinvertebrate habitat. Following mobilization of the bed material during the snowmelt runoff period, a new armor layer is formed on the bed of the river in both the riffles and the runs, and provided that the subsequent post-runoff discharges are less than about 4,800 cfs, the armor layer will be stable throughout the site.

Transient responses are primarily related to the fine sediments (mud) (D_{50} less than 0.06 mm) that is deposited on, and eroded from, the stable gravel-cobble riverbed at different locations in the site when discharges in the river are less than about 4,800 cfs (discharge that is equaled or exceeded about 15 percent of the time). Fine sediment is supplied during post-runoff summer thunderstorms over the lower elevation portions of the basin upstream of the 15-MR that are underlain by highly erodible, sedimentary rocks. Discharges in the river during this period (baseflows) are controlled by upstream reservoir releases and irrigation diversions, and generally range from about 800 cfs. During events when fine sediment is supplied to the reach, mud is deposited on the gravel and cobbles in areas where velocity and shear stress are less than about 2.5 fps and 0.03 lb/ft^2, respectively. At locations where velocity and shear stresses are higher than 2.5 fps and 0.03 lb/ft^2 respectively, mud is not deposited even when there is a supply of fine sediment, and previously deposited mud is re-entrained (Chow, 1958; Smerdon and Beasely, 1961; Partheniades, 1965; Graf, 1971; Partheniades and Kennedy, 1973; Haralimpedes et al., 2003). Because the shear stress and turbulence are generally higher in riffles than runs, riffles tend to be more sensitive to small changes in discharge than runs. Removal of previously deposited mud may occur in the riffles during small increases in discharge associated with the summer thunderstorms. However, even if it is not deposited, the fine sediments in transport may still affect periphyton and macroinvertebrate communities by abrasion or scouring.

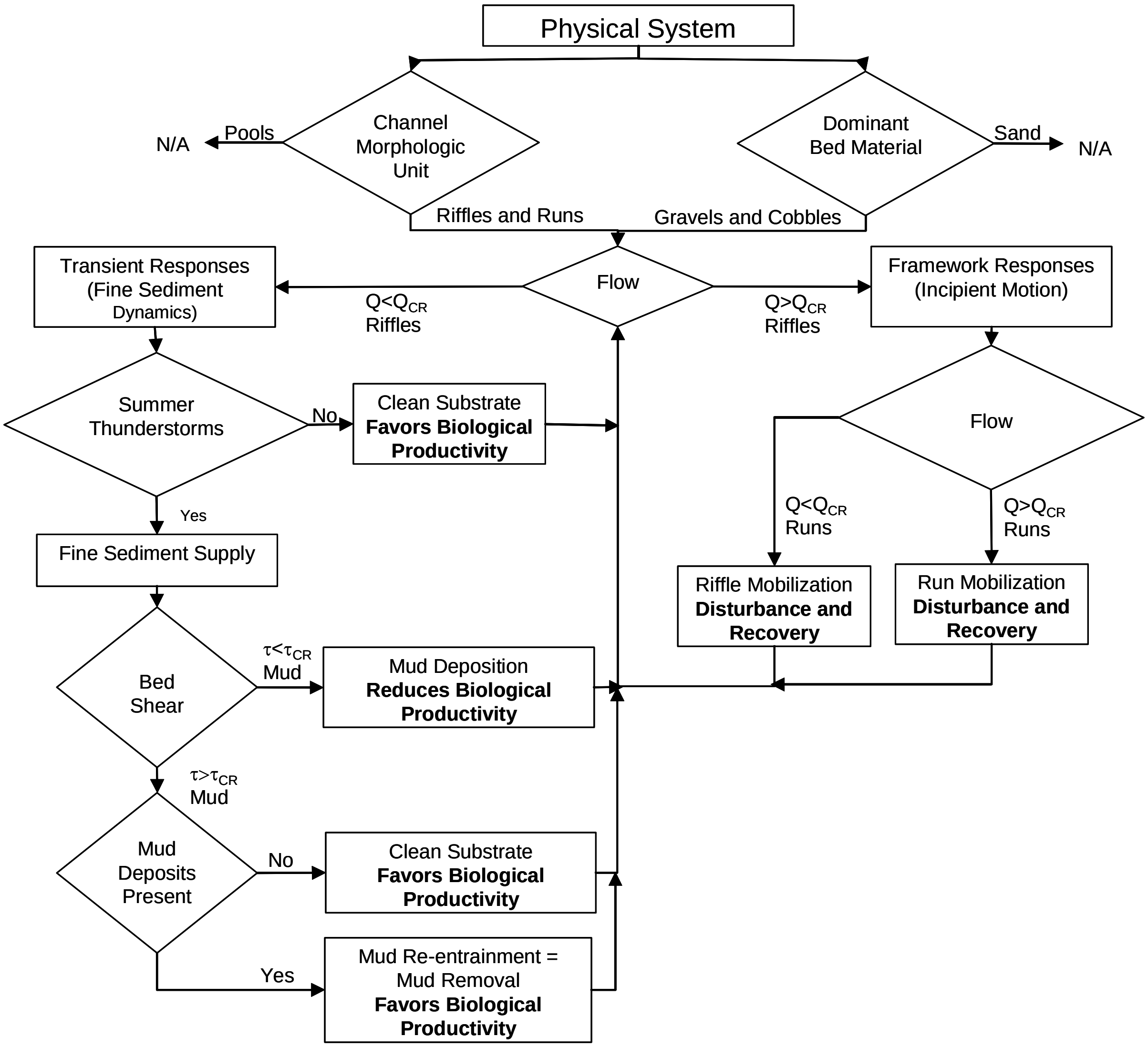


Figure ES-4. Flow chart that summarizes the physical processes that are related to sediment mobilization and mud deposition that create biological disturbances in the 15-MR.

Observations at the site since 1999 indicated that regardless of discharge, six classes with varying amounts of deposited fine sediment were present at the site (Table ES-1, Figure ES-5). These classes were mapped at the study site and the class boundaries were correlated with predicted shear stress from the hydrodynamic model.

The results of the 2-D modeling were used to compare surface area differences for individual classes for a range of flow regimes. The range of flows simulated for this study included baseflows from 800 through 1,400 cfs and then intermediate flows of 2,000 and 4,800 cfs. Comparison of the data for the individual classes shows that there are substantial increases in the mud-free area at the site with an increase in discharge from 800 to 1,100 and from 1,100 to 1,400 cfs (Figure ES-6). This same comparison of classes shows the amount of habitat that is cleaned and that changed from the class 2 and class 3 types, which have thick mud deposits, to a cleaner system to provide more habitat for macroinvertebrates and periphyton. These predicted changes in mud-free zones can be used as a basis for developing baseflow management alternatives to reduce the impact of thunderstorm events in the summer, and provide more productive, clean area for periphyton and macroinvertebrates.

This approach can be used to compare a variety of flow regimes during baseflows to determine changes in the amount of cleaned habitat for the lower trophic levels. An analysis of undepleted baseflows based on the STATEMOD hydrology model shows that undepleted flow during the August through October period was higher than the present flow regime. This indicates that there was an increase in potential habitat area for macroinvertebrates and periphyton under the historical flow regime. Management alternatives that provide for slightly higher flows than the current flow regime during this period would provide greater habitat area, and therefore, greater productivity, provided that the increased flows did not cause bed material mobilization.

In the winter-spring baseflow period (November-April), the current flows are, with the exception of the month of April, higher than the undepleted flows. Given that there are a number of precipitation-induced elevated turbidity events during the winter baseflow period, it is likely that the increased flows provide an increased area of mud-free substrate for the biota over what would have been present historically during this component of the annual hydrograph.

Table ES-1. Classification used to map mud deposits at the Clifton site.

Class	Description
1	Subaerial thick mud deposits on channel and bar margins
2	Subaqueous thick mud deposits totally covering dead algae
3	Subaqueous mud deposits with some dead algae visible
4	Subaqueous mud with alive green algae
5	Dense algal growth with some mud trapped in the algae
6	Clean gravels and cobbles with no mud present

Class 1

Class 2

Class 3

Class 4

Class 5

Class 6

Figure ES-5. Photographs of the mud classes that were used to map the spatial distribution of the mud deposits at the Clifton and Corn Lake sites in the 15-MR.

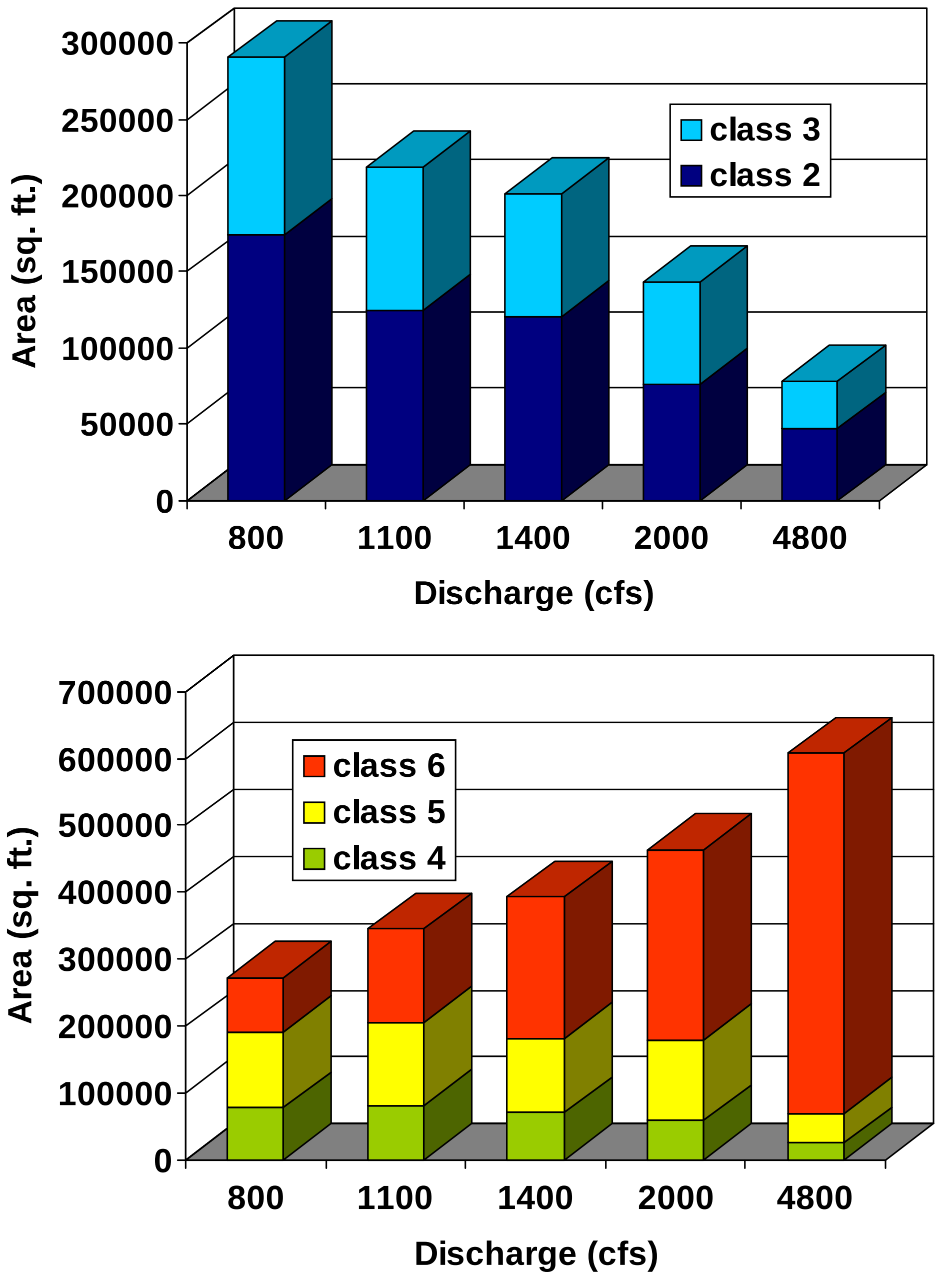


Figure ES-6. Bar graphs showing the areas occupied by each of the mud classes at discharges of 800, 1,000, 1,400, 2,000, and 4,800 cfs at the Clifton site.

Biological Investigations

The biological portion of this joint investigation monitored biotic community characteristics at riffle-run habitat units from May through October during the years 1999 through 2003. The biological parameters primarily included periphyton and benthic macroinvertebrate sampling; however, small-bodied fish were also sampled on one occasion. Periphyton and benthic macroinvertebrates are two components that can be used as indicators of primary and secondary productivity and form the basic food web components for Colorado pikeminnow prey. Osmundson (1999) hypothesized that increases in productivity levels (mainly through increased productivity in run habitats) can lead to increases in population numbers for species at higher trophic levels. The biological component of this study can be used in conjunction with the physical responses to flow regime to project limitations to primary and secondary trophic levels in the 15-MR of the Colorado River (Figure ES-7).

A number of metrics (indices) were employed to analyze periphyton and macroinvertebrate data. Measurements used in the analysis of periphyton data included: diversity, density, taxa richness and biovolume. Metrics used to interpret macroinvertebrate data included; diversity, evenness, EPT index, FBI index, taxa richness, density, biomass and analysis of functional feeding groups. Many of these metrics are part of routine macroinvertebrate analysis procedures (Barbour et al. 1999). To address the objectives of this study, greater emphasis was placed on taxa richness, density and biomass (biovolume for periphyton). These three metrics were used in regression analysis with physical variables to determine the relative importance of physical variables on the macroinvertebrate and periphyton communities.

Periphyton data were highly variable between sampling occasions, site locations and even among repetitions. Riffle habitat produced the highest yearly values for most of the applied metrics; however, most of the lowest metric values were also produced by this habitat. Results of regression analysis identified several variables that were significant ($p<0.1$) predictors of periphyton metrics. These variables included; increase in mean daily turbidity prior to sampling, mean daily discharge, percent change in NTU since last sample and number of days since last threshold (>400 NTU) event. The relative importance of these variables was dependant on habitat and the metric used to describe the periphyton community. The results suggested that periphyton communities during the study period were primarily influenced by recent environmental conditions.

Macroinvertebrate standing crop at each site was determined using density and biomass. Macroinvertebrate density was reported as the mean number of macroinvertebrates/m^2 found at each location. Densities were compared between sites for each sampling occasion. Biomass was reported as the mean dry weight of macroinvertebrates/m^2 at each site location. Biomass values provide standing crop and production related information in terms of weight of macroinvertebrates produced by each habitat.

Density of invertebrates in riffles ranged from 1.3 to 24.3 times higher than density in run habitat. On average the density of invertebrates in riffles was 6.9 times higher than the density in run habitat. Biomass values showed a similar relationship. Biomass of invertebrates in riffles ranged from 0.9 to 85.8 times the biomass in run habitat. On average the biomass of invertebrates in riffles was 8.5 times the biomass in run habitat.

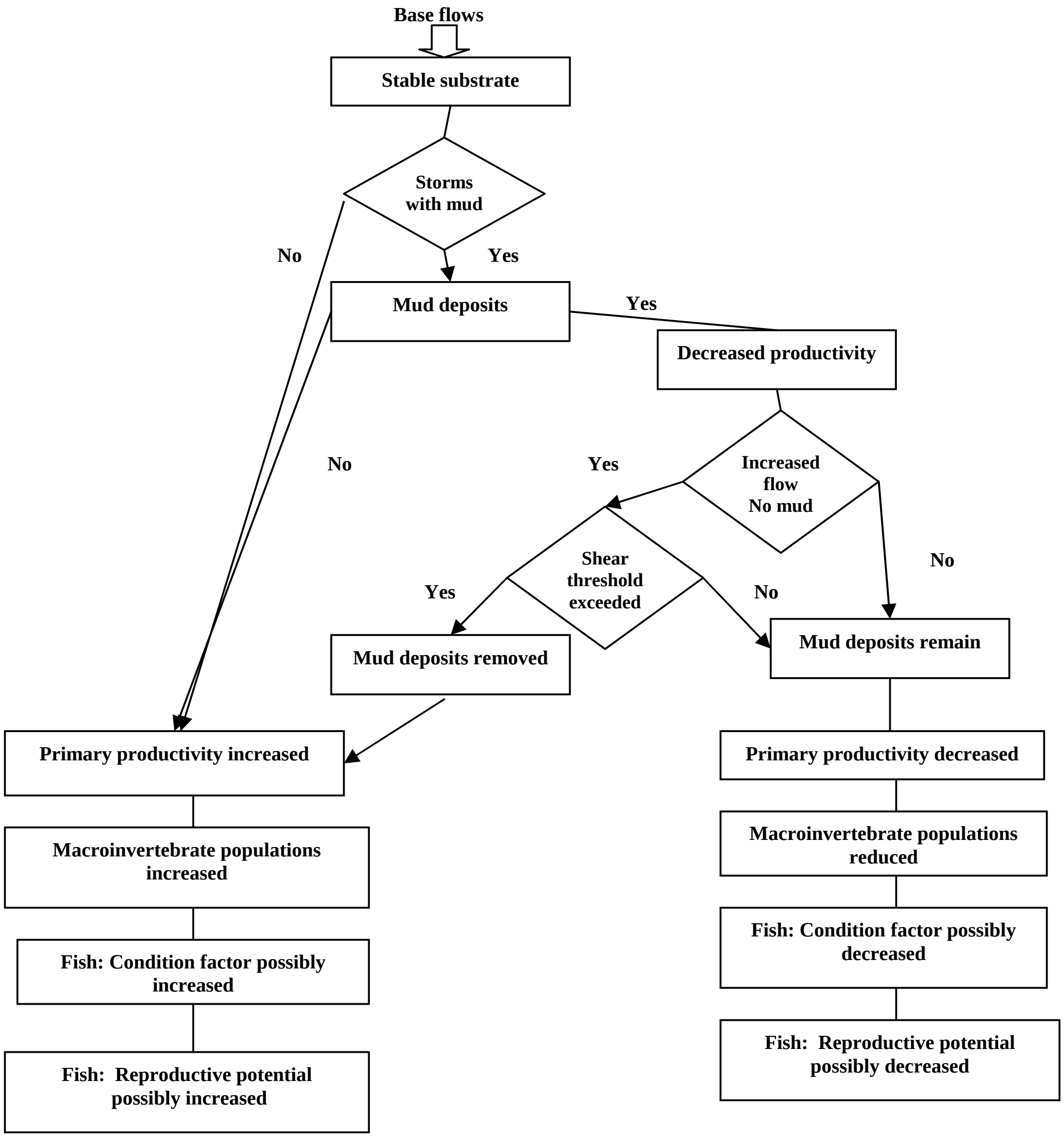


Figure ES-7. Biological response to physical processes in riffle and run habitat in the 15 MR.

Results of regression analysis identified several variables that were significant ($p<0.0.05$) predictors of macroinvertebrate richness, density, and biomass in riffle and run habitat. The increase in mean daily turbidity prior to sampling was found to have a significant ($p<0.1$) negative impact on all biological responses, but was not used in the regression model because it conflicted with other turbidity measurements that were similar. Other variables included the Log (number of days since the last threshold (>400 NTU) event), percent change in turbidity, number of days below base turbidity (<50 NTU), Log (average daily discharge), annual peak flow, and the interaction between annual peak flow and number of days below base turbidity. Of these physical variables, the number of days below base turbidity (50 NTU) was most often significant ($p<0.05$). Annual peak flow was not a significant variable in any of the regression models for macroinvertebrates or periphyton.

Results of the biological portion of this study indicate that all trophic levels are present and exist in a range of structure and function that would be considered acceptable given the restrictions caused by physical processes. This potential for production was observed during a period of relatively low, clear, stable flows following peak flows during the year 2000, and during the relatively low stable flows resulting from drought conditions in 2002..

Previous research on the 15-MR of the Colorado River (Lamarra 1999) found that primary and secondary production occur at higher rates in riffle habitats as opposed to run habitat. Lamarra (1999) and Osmundson (1999) also hypothesize that higher flows during the runoff period may result in higher primary and secondary productivity thereby indirectly increasing fish condition and carrying capacity. The results produced by this study suggest that a number of variables (including flow regime) may play an important role in determining standing crop and ultimately productivity. Higher current velocities associated with riffle habitat contribute to a greater density and biomass of periphyton and macroinvertebrates during periods of low stable flow. The increase in the standing crop in riffle and run habitat coincided with flow stability (or decreasing flows) and a decrease in turbidity. Based on the findings of this research it seems likely that a variety of factors (turbidity, frequency and intensity of storm events, deposition of sediments, specific runoff characteristics, scouring of sediments, flow stability, etc.) may influence primary and secondary productivity in the 15-MR of the Colorado River.

Table of Contents

List of Figures

List of Tables

1 INTRODUCTION

The Upper Colorado River near Grand Junction, Colorado and the 15-Mile Reach (15-MR) (Figure 1-1) provide habitat for numerous species of aquatic organisms including fish. Fish populations in this section of the Colorado River include several native species (including two federally listed fish species) that have been extirpated from much of their original habitat. The primary focus of this investigation was to address the hypothesis that the current peak flow regime is limiting certain ecological components required for the recovery of the listed native fish species.

Physical and biological requirements for peak flows within the Upper Colorado River have been summarized by Osmundson et al. (1995) and Osmundson et al. (2002). These include: channel maintenance, flushing of fine sediment from gravels and cobbles that form the bed of the river, control of vegetation encroachment into the channel, entrainment of organic debris from the floodplain , improvement of substrate conditions for spawning and reproductive success, and perhaps control of small non-native fish abundance.

A preliminary assessment of the carrying capacity for adult Colorado pikeminnow suggested that long-term viability goals for recovery of this species might not be met due to limitations in adult habitat capacity (Osmundson 1999; Osmundson et al. 2002). Osmundson (1999) postulated that historical carrying capacity was higher than the present, and that potential causes for the decreased capacity included: reduction in adult range, reduction of suitable prey, a reduction of quantity of prey, and a reduction of optimal or preferred physical habitats. He further pointed out that the changes could be the result of: (1) diversion structures blocking upstream passage of the fish and reducing water temperatures, (2) non-native species, (3) storage projects reducing the magnitude of the spring peak flows and reducing the flushing of fine sediments from the coarser gravels, and (4) irrigation diversions and bank stabilization projects that reduced the quantity of seasonally-preferred mesohabitats. Since run habitats form the majority of the meso-scale geomorphic units that comprise the channel environment in the upper Colorado River, Lamarra (1999) hypothesized that an increase in productivity of the runs could lead to a significant increase in total productivity for the river.

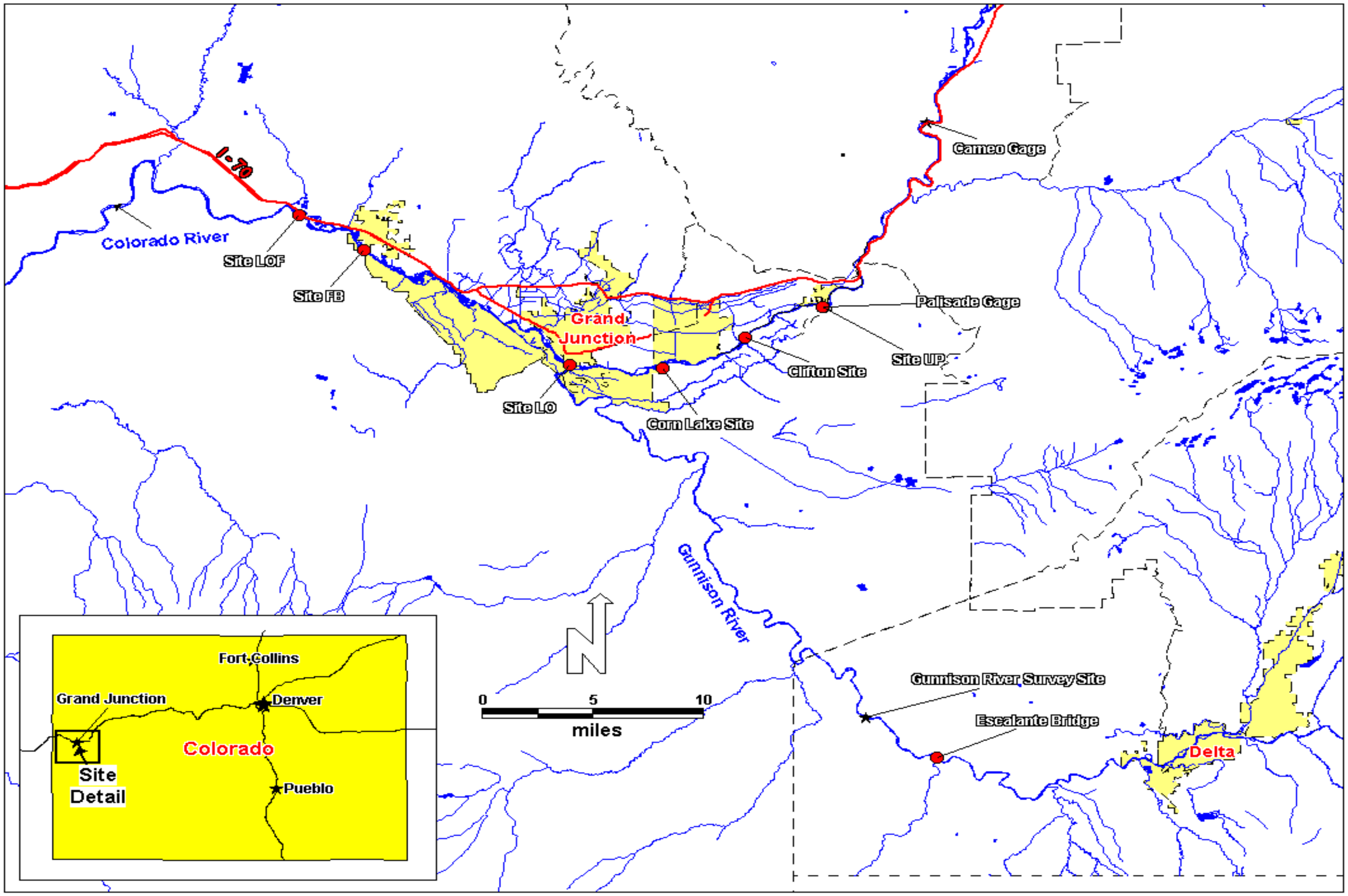


Figure 1-1. Map showing the locations of the Colorado and Gunnison Rivers and the locations of the MEC/MEI data collection and analysis sites on both rivers. Also shown are the locations of the Cameo and Palisade gages.

Water resource development projects in the Upper Colorado River (UCR) basin upstream of the 15-MR commenced in the 1920's and by about 1950 controlled approximately 45 percent of the annual streamflow (Pitlick et al. 1999). Comparison of log-Pearson III flood frequency curves developed from annual peak flow records at the USGS Palisade gage (No. 090106000) that covered the period from 1902 to 1933, and the USGS Cameo gage (No. 09095500) that covered the period from 1950 to 2000 showed that there has been a 30 to 40 percent reduction in the magnitude of the 2- and 5-year recurrence interval peak flows (Pitlick et al. 1999, and this study). The current 2-year peak discharge is about 18,000 cfs and the 5-year peak discharge is about 27,000 cfs. Suspended sediment concentrations at the gages have not changed appreciably (Pitlick and Wilcock 2001) as a result of the upstream dam construction in the last 50 years because of the high supply of sediment from the lower elevation portions of the basin that are underlain by highly erodible sedimentary rocks (Iorns et al., 1965; Van Steeter and Pitlick 1998; Liebermann et al. 1989; Spahr et al. 2000). Total sediment loads have been reduced because of the reduced flows (Pitlick and Van Steeter 1998).

Investigation of the relationships between flows, sediment loads and habitat requires that the temporal nature of the relationships be recognized and incorporated. In general terms, the annual hydrograph can be broken down into low-flow and high flow periods. The low-flow periods include late summer, fall and winter baseflows that extend from about August to the end of April. The high-flow period includes the rising, peak and falling limbs of the annual snowmelt hydrograph that usually extend from May to the end of July. The bulk of the annual sediment load is transported during the high-flow period when there is transport of both the suspended load and bedload (Pitlick et al. 1999). These flows are, therefore, morphologically important. During the low-flow periods there is transport and deposition of volumetrically less substantial amounts of sand, silt and clay that have little morphological importance.

Some of the sediment transport-related functions of peak flows have been addressed in other studies and investigations (Osmundson et al. 1995; Osmundson et al. 2002). Pitlick and Van Steeter (1994); Pitlick et al. (1997); Van Steeter and Pitlick (1998); Pitlick and Van Steeter (1998); Pitlick et al. (1999); and Pitlick and Cress (2000) have addressed the issue of channel maintenance in relation to changes in flow regimes due to upstream water developments. The results of these channel-maintenance studies indicate that, since 1950, there has been about a 30 percent reduction in the annual peak discharges at the Cameo gage on the Colorado River. The reduced peak discharges and the reductions in suspended sediment loads have resulted in about a 10 to 15 percent reduction in channel width and about a 25 percent reduction in side channels and backwaters. However, Pitlick et al. (1999) also concluded that the current channel morphology was in equilibrium with the current peak-flow regime and suspended sediment load. Therefore, it can be concluded that the current peak-flow regime (1950 to the present) is adequate in terms of both magnitude and frequency to maintain the present channel morphology and presumably the associated habitats since habitats are formed and maintained by the in-channel processes. Therefore, it is unlikely there will be further loss of channel margin and in-channel habitats if the current flow regime is maintained.

Peak flows also can affect spawning habitat. High peak discharges that build the mesoscale spawning bars, but do not actually create the microscale-spawning habitat, are required with some as yet undetermined frequency. Previous investigations of hydrodynamic conditions required for Colorado pikeminnow spawning in the Yampa (Harvey et al. 1993; Mussetter et al. 2002), and Green Rivers (Harvey and Mussetter 1994; Harvey et al. in review 2002), have demonstrated that spawning occurs under very similar hydrodynamic conditions at a number of sites where the macroscale characteristics of the reaches that contain the spawning bars are very dissimilar. Hydrodynamic conditions required for spawning occur during recessional flows following the peak of the snowmelt hydrograph at all of the sites. Development of a physical process-biological response model (PRM, Harvey et al. 1993) for pikeminnow spawning habitat formation and maintenance provides a means for evaluating the spawning potential in the 15-MR. Based on the PRM, it is highly unlikely that the 15-MR in its natural state would have provided pikeminnow spawning habitat, and the fish were more likely to have spawned upstream of the 15-MR in the Debeque Canyon reach of the river.

It has been postulated that removal of fines by peak flushing flows will result in an increase in biotic productivity, and thus an increase in the overall carrying capacity for listed native fish species in the Upper Colorado River (Lamarra 1999; Osmundson and Scheer 1998; Osmundson et al. 2002). A number of previous studies on coldwater, salmonid streams have shown that fine sediment (sands and very fine gravels) cannot be winnowed or flushed from appreciable depths within the bed material without mobilization of framework gravels (Diplas 1994; Kondolf and

Wilcock 1996; Milhous 1998). Pitlick et al. (1999) concluded that incipient-motion conditions (defined as a low but measureable sediment transport rate) for the gravel-and-cobble sediments that comprise the bed material of the Colorado River within the 15-MR occurs at about half the bankfull discharge (about 10,500 cfs). They further concluded that general mobilization of the bed material required to flush the finer sediments from the framework gravels takes place at a discharge that corresponds with the bankfull discharge (about 22,000 cfs). However, Downes et al. (1997) have argued that generalized relations for predicting bed mobilization are not particularly meaningful as measures of disturbance frequency for ecological purposes because the disturbance effects occur at a microscale level that is not adequately described by the generalized relations. Therefore, there may be localized areas within the channel, such as riffles, where incipient conditions and bed mobilization occur at much lower discharges (Harvey et al. 1993).

Within the context of this investigation of the 15-MR, fine sediment is defined primarily in terms of very fine sand, silt, and clay (which are referred to as mud in this report) that are derived from the sedimentary rocks that crop out in the lower elevations of the Upper Colorado River (UCR) basin (Iorns et al. 1965; Van Steeter and Pitlick 1998; Spahr et al. 2000). Suspended sediment concentrations at all flow levels have not changed appreciably at the mainstem gaging stations within the UCR basin in the last 50 years, although suspended sediment loads have been reduced because of upstream flow regulation (Pitlick and Wilcock 2001). Osmundson et al (2002) suggested that inputs of fine sediment to the UCR may have increased during historic and recent times as a result of land use practices (grazing, irrigation return flows, road building, off-road vehicle use). However, sediment delivery to the Upper Colorado River has always been high because of the combined effects of erodible rocks and a semi-arid climate where sediment yield is maximized (Langbein and Schumm 1958; Dendy and Bolton 1976). Jordan (1891) noted the increased fine sediments and turbidity in the lower reaches of the Colorado River and reported "lower down they become gradually turbid and yellow and finally the Colorado becomes one of our muddiest streams." Iorns et al. (1965) concluded that the average annual unit suspended discharge from the Grand Division (upstream of the Gunnison River) was on the order of 2,400 tons per square mile. However, the area between the Cameo gage and the Roaring Fork had an average annual unit sediment discharge of about 4,700 tons per square mile, and major sediment sources were the Roan and Parachute Creek drainages. It is also likely that the pervasive arroyo cutting throughout the Colorado Plateau that commenced in the mid 1800s (Cooke and Reeves 1976; Wells 1988; Bolling and Wells 1990; Schumm et al. 1984) may have caused a period of appreciably higher suspended sediment concentrations prior to the 1940s. Analysis of suspended sediment records within the UCR basin (Colorado, Green and San Juan Rivers) by Thompson (1982, 1984) and Gellis et al. (1991) demonstrated that there was a statistically significant reduction in the suspended sediment loads without a commensurate change in discharge in the early 1940's prior to the construction of the upstream dams. Hadley (1974, 1977) and Lusby (1970) attributed some of the reduction to reduced numbers of livestock and the construction of numerous sediment detention structures. However, Gellis et al (1991) concluded that the reduced sediment loads were due to arroyo evolution that ultimately leads to back filling and sediment storage rather than sediment delivery from the incised drainages. Schumm and Hadley (1957), Patton and Schumm (1981), Wells (1988) and Balling and Wells (1990) have reported the widespread occurrence throughout the Colorado Plateau of pre-historic cycles of arroyo cutting and filling that appear to be related to changes in precipitation patterns and the exceedence of geomorphic thresholds. Based on the suspended sediment data from the latest period of arroyo instability, the pre-historic cycles of arroyo cutting and filling must also have been responsible for significant changes in suspended sediment loads in the UCR.

The muds (about 40 percent fine sand and 60 percent silt and clay) that are introduced to the river primarily by summer thunderstorms that have little impact on the discharge in the river after the snowmelt-driven peak flows (generally when the discharge is less than about 2,000 cfs) tend to deposit on and among the gravels and cobbles that form the lower banks, and the low-velocity margins of the bed and bars in the river. At higher flows, some mud may be deposited on the channel margins (high on the banks). These areas are dry for the majority of the year (based on the mean daily flow record at the Palisade Gage, flows are equal to or less than 2,000 cfs 60 percent of the time). Therefore, these dry channel margins are not a factor in determining the biological productivity of the site.

The biological role of suspended sediment and sediment deposition is extensively complex and only partially understood. Yet, Judy et al. (1984) described sedimentation as the most important factor that is limiting fish habitat in the U.S. The biological portion of this study analyzed two components of the food chain - periphyton and macroinvertebrates. These components were quantitatively monitored to assess the impact from sedimentation and suspended sediments.

Analysis of benthic macroinvertebrate samples has become a widely accepted tool used to monitor aquatic conditions in lotic environments (Winner et al. 1980; Plafkin et al. 1989; Cairns 1990; Cairns and Pratt 1992; Rosenberg and Resh 1992). Benthic macroinvertebrate community structure and function are products of the physical and biological influences present in the environment. Life history of aquatic macroinvertebrates is species dependant; however most species in the 15-MR have an aquatic stage or life span of one year or less. The change in abundance of each species from year to year reflects the influence of physical and biological processes on which each species depends. The dominant force contributing to the structure of aquatic macroinvertebrate communities is dependent upon the time of year, adaptations of the given macroinvertebrate species, and/or magnitude of disturbances (Poff and Ward 1989). The flow regime of a stream is usually considered to be one of the most important factors that influence aquatic communities (Poff et al. 1997).

Macroinvertebrate species that evolved in the Colorado River evolved with a snowmelt hydrograph. In general, these species have developed life cycle strategies that help them avoid the adverse conditions associated with snowmelt runoff. The peak flows associated with snowmelt runoff are often avoided by macroinvertebrates by timing their lifecycles so that they are in either the egg or adult stage. Most growth of nymphs and larvae takes place during warm, stable aquatic conditions that occur during the summer months. Although the timing and magnitude of annual peak flows can influence the structure of biological communities, there are other physical processes that influence biological communities during relatively stable periods of the hydrograph.

The addition of fine sediments in suspension or by deposition has been found to be an important variable that can directly (and indirectly) impact aquatic organisms and alter aquatic food webs (Henley et al. 2000). Sediment in transit reduces light transmission and can have abrasive qualities, and the deposition of fine sediment reduces benthic habitat and can smother benthic organisms. Sedimentation and turbidity can potentially impact aquatic food webs at each trophic level (Henley et al. 2000). Impacts at the lower levels may result in a cascading effect that ultimately alters predator populations.

Researchers are in general agreement that the addition of fine sediment to a lotic system impacts most biological components of that system (Cordone and Kelley 1961; Waters 1995). The influence of sediment on primary production has probably received less attention than other components of the aquatic food chain; however, most studies agree that fine sediments can have a negative impact on periphyton communities. Newcombe and MacDonald (1991) indicate that reductions in algae are generally related to the effect of suspended sediments on light penetration and the process of scouring. Waters (1995) states that deposition of sediment on substrate surfaces may also reduce primary production. The light reduction and abrasive qualities of sediments in suspension have been found to cause elevated levels of drift in many species of aquatic insects (Ciborowski et al. 1977; Culp et al. 1986). More recent studies have suggested that concentration of suspended sediments and duration of exposure are both important factors when considering the response of benthic macroinvertebrates to suspended sediments (Doeg and Milledge 1991; Newcombe and MacDonald 1991). The deposition of fine sediment and associated alterations and impacts to macroinvertebrate community structure has been well documented (Kohlhepp and Hellenthal 1992; Henley et al. 2000). Although the focus of this study did not include monitoring the effect of sediment on fish, there have been numerous studies that describe the negative impacts of fine sediment on different species of fish at various life stages (Cordone and Kelley 1961).

The original emphasis of this investigation was an evaluation of the role of peak flows on fine sediment movement and deposition on and within the substrate matrix in the 15-MR of the Colorado River and determination of the effects on aquatic biota. As this investigation progressed, emphasis was also placed on evaluating the flow-fine sediment relationships and potential impacts on foodweb components that would likely influence carrying capacity for Colorado pikeminnow. A single riffle-run habitat unit within the 15-MR was jointly investigated over the course of the annual hydrograph for five years by a team comprised of stream ecologists, geomorphologists and hydraulic engineers.

1.1 Objectives

1.1.1 Physical Process

The primary objective of the physical process portion of this investigation was to investigate the interactions between the supply of fine sediment (primarily fine sand, silt and clay) from the upstream watershed and the hydrodynamic conditions within the reach for a range of flows that define the annual hydrograph. A second objective was to investigate the influence of these interactions as they relate to the deposition and erosion of fine sediments (mud) within the reach. Specific areas that were investigated included:

- Factors that control the supply of fine sediment to the 15-MR and the timing of sediment supply,
- The hydrodynamic conditions within the reach that permit mud deposition and the resulting spatial distribution of the mud deposits within the reach,
- The hydrodynamic conditions within the reach that permit general mobilization of the gravel and cobble that constitutes the bed material in the riffles and runs,
- The range of flows required to deposit and remove fine sediments (mud) from the bed of the channel, and
- Whether it is necessary to mobilize the underlying coarse-grained bed material for flushing of accumulated fine sediment (mud) to occur.

1.1.2 Biological Process

The initial objective of this investigation was to evaluate whether the current peak flows in the 15 Mile Reach of the Colorado River limit the recovery of listed fish and the aquatic community on which they depend. Secondary objectives were to define and describe the ecological response to high flow regimes and other physical processes that might be influencing primary and secondary production, structure and function. The specific objectives for the biological portion of this study included:

- Determine if primary and secondary productivity and standing crop are dependent on the magnitude of annual peakflow.

- Determine if there is a relationship between turbidity produced by summer thunderstorms in the post-runoff period and alterations in primary and secondary standing crop in identified mesohabitat units.

- Describe any difference in primary and secondary production between two major habitat types (run and riffle) in the 15-Mile-Reach of the Colorado River.

- Describe any seasonal or annual patterns for standing crop of lower components of the food chain in the 15-Mile-Reach of the Colorado River.

- Determine if there are differences in primary and secondary production in different reaches of the Upper Colorado River downstream from Palisade, Colorado.

- Describe relationships between primary and secondary productivity and listed native fish population carrying capacity.

2 METHODS

This chapter provides a description of the study areas in the 15-Mile Reach, the 18-Mile Reach and on the Gunnison River, and the methods that were used in the physical process and biological investigations conducted for this study.

2.1 Study Area

The 15-MR of the Colorado River extends from the Grand Valley Diversion at Palisade to the confluence with the Gunnison River (Figure 2-1). In general, the reach can be characterized as being bedrock-confined along the left (south) bank, and confined by the historic floodplain and terraces along the right (north) bank. Low, local levees have been constructed along the right bank to prevent flooding, and in a number of locations, various forms of bank protection, including rock riprap, rock dikes and concrete rubble, have been installed to prevent further bank erosion. Following a boat reconnaissance of the 15-MR in 1999, the Clifton Water Treatment Plant (hereafter referred to as the Clifton site) site was chosen as being representative of the geomorphic characteristics of the 15-MR. Data and analyses were collected and conducted, respectively, at two locations: the Clifton and Corn Lake sites. The bulk of the data were collected at the Clifton site, and the data at the Corn Lake site were collected to verify the findings from the Clifton site. The Colorado Division of Wildlife (CDOW) conducted topographic and bathymetric surveys of the Corn Lake site in 2000 for the purposes of developing a two-dimensional (2-D) hydrodynamic model of the site (Stewart 2001). These surveys were supplemented by additional topographic surveys by Mussetter Engineering, Inc. (MEI) for this project.

2.1.1 Clifton and Corn Lake Sites

The Clifton site is about 2,200 feet long and encompasses a large mid-channel bar that becomes submerged at a discharge of about 4,800 cfs, as well as a large cross-channel riffle in the middle of the site and a small cobble bar at the upstream end of the site located near the left bank (Figure 2-2). The channel is confined by outcrop of Mancos Shale along the left bank (looking downstream) and the Colorado River floodplain along the right bank. A low elevation

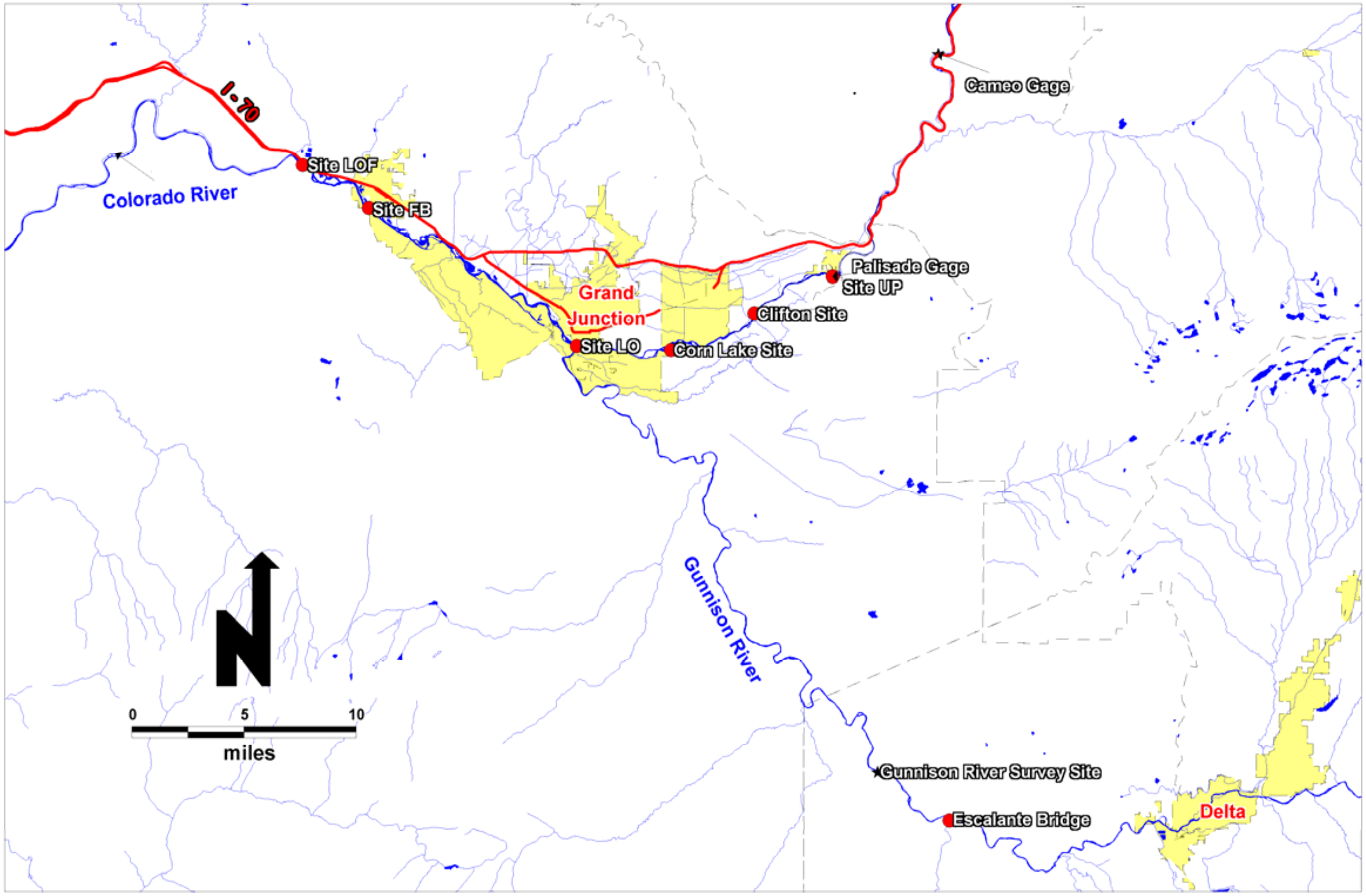


Figure 2-1. Map showing the locations of the Colorado and Gunnison Rivers and the locations of the MEC/MEI data collection and analysis sites on both rivers. Also shown are the locations of the USGS Cameo and Palisade gages.

Figure 2-2. Aerial photograph of the Colorado River at the Clifton site showing the geomorphic elements of the site.

levee was constructed historically along the right bank to prevent overbank flooding. Within the site, the mid-channel bar causes a split-flow condition at flows below 4,800 cfs. Downstream of the large cross-channel riffle in the middle of the site is a relatively deep run.

The Corn Lake site is about 2,000 feet long and encompasses a small mid-channel bar that becomes submerged at a discharge of about 2,000 cfs, as well as a large cross-channel riffle at the downstream end of the site (Figure 2-3). The channel is confined by a terrace along the left bank (looking downstream) and a cutoff point bar surface along the right bank. Within the site, the mid-channel bar causes a split-flow condition at flows below 2,000 cfs. Up and downstream of the large cross-channel riffle at the downstream end of the site are relatively deep runs.

The majority of the biological sampling was conducted at the Clifton site in two habitat types: 1) Cross Section 5 (riffle habitat) and, 2) Cross Section 2 (run habitat). These initial locations for periphyton and macroinvertebrate sampling were selected in 1999. The sample location at Cross Section 5 (Site 5) was established in the center of a typical riffle for that reach (Figure 2-4). The sample location at Cross Section 2 (Site 2) was located in typical run habitat (Figure 2-5). All macroinvertebrate and periphyton samples were collected at the designated cross sections during each sampling occasion. The Clifton site was used during 1999, 2000, 2001, 2002, and 2003.

2.1.2 Synoptic Sites

During 2001 other synoptic sampling sites were included that ranged from the upper end of the 15-MR downstream into the 18-MR section of the Colorado River and one site on the Gunnison River (Figure 2-1). The synoptic site locations are described as follows:

Site UP: This site was located in the upper 15-MR approximately 0.5km downstream from the Grand Valley Diversion.

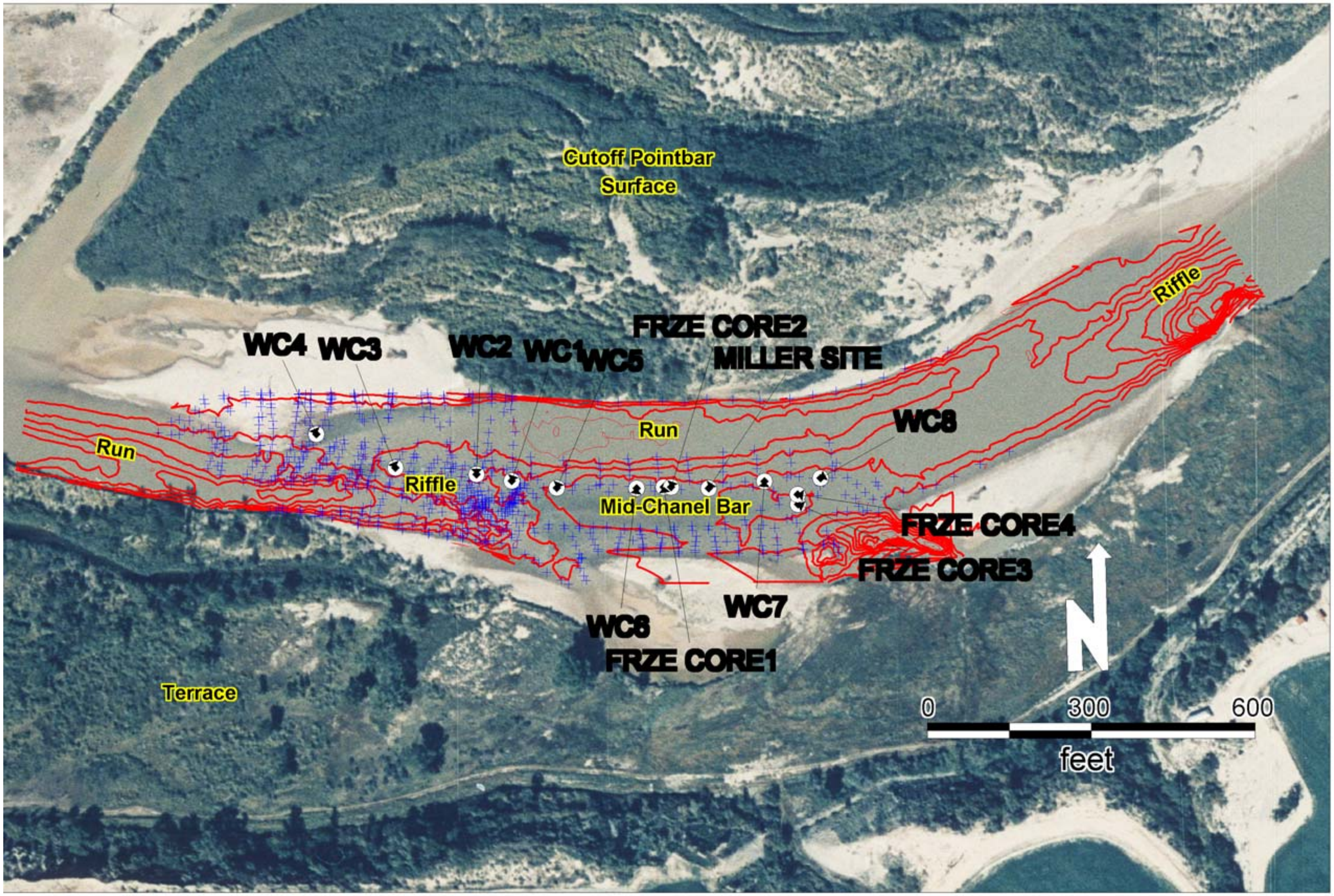


Figure 2-3. Aerial photograph of the Colorado River at the Corn Lake site showing the geomorphic elements of the site, as well as the in-channel topography and the locations of the sediment samples and freeze cores.

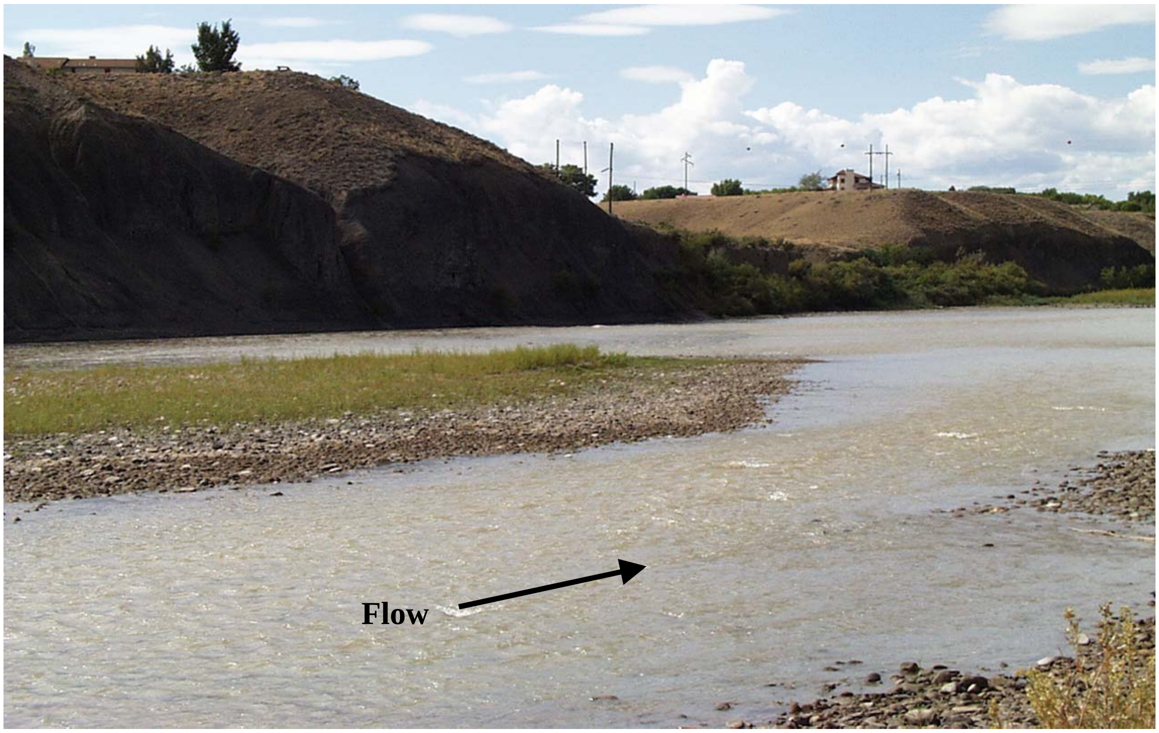


Figure 2-4. Riffle habitat (Site 5) at the Clifton site on the Colorado River.

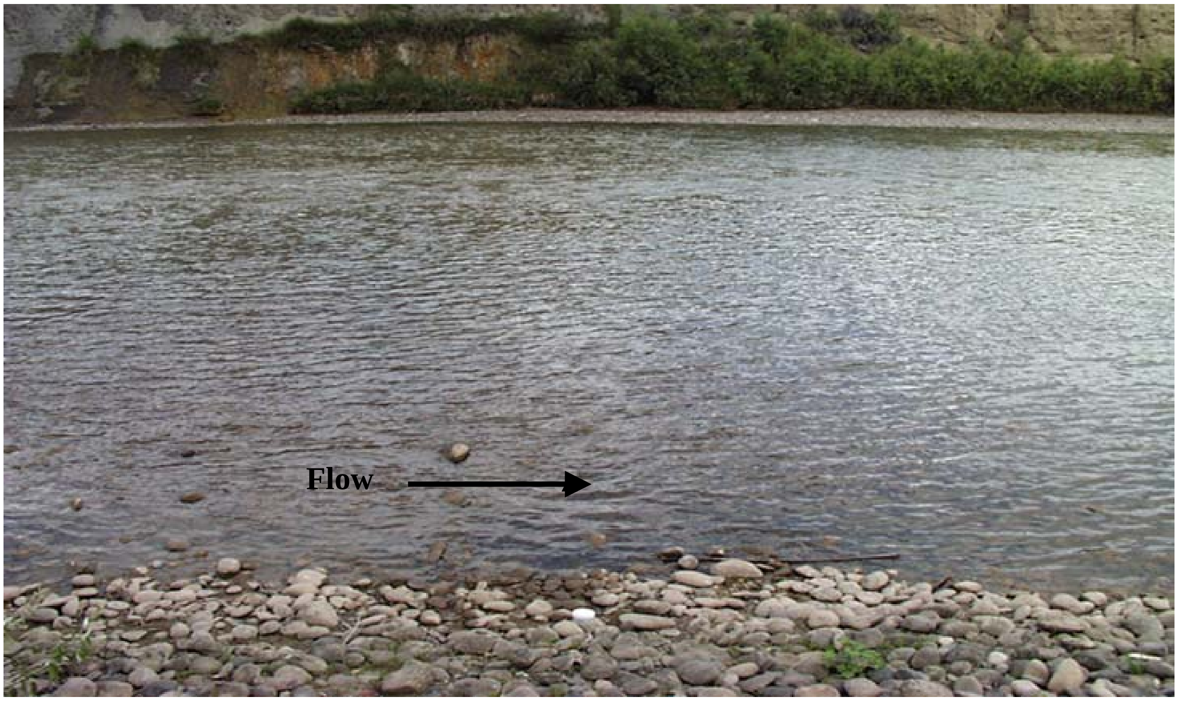


Figure 2-5. Run habitat (Site 2) at the Clifton site on the Colorado River.

M-46: This point was located in riffle habitat near Site 5 at the Clifton site. Three replicate macroinvertebrate samples were taken at this location on 28 Aug 01, for the purpose of comparing macroinvertebrate communities at locations with different velocities within the same riffle.

Site CL: This site was located approximately 1.5 km downstream of Corn Lake in the middle of the 15-MR in a section of the river where fish populations had been intensely studied by the Colorado Division of Wildlife.

Site LO: This site was located in the lower 15-MR of the Colorado River in a riffle-run complex approximately 200m upstream from the confluence of the Gunnison and Colorado rivers.

Site FB: This site was located in the 18-MR immediately downstream from the highway bridge that crosses the river in the town of Fruita, Colorado.

Site LOF: This site location was chosen in the 18-MR at a river access point between the towns of Fruita and Loma.

Site GUN-ESC: This was the only site located in the Gunnison River. The specific location was immediately below the Escalante Bridge.

2.2 Physical Process Methods

This section of the report identifies the types of data that were collected for the physical process investigation and the methods that were used to collect and analyze the data, as well as the sources of data that were obtained from outside of the Clifton and Corn Lake sites.

2.2.1 Hydrology and Suspended Sediment Analyses

Flood-frequency curves, using a log Pearson Type III distribution, were developed for the peak-flow record for the Cameo and Palisade gages using the U.S. Army Corps of Engineers HEC-FFA computer program (COE 1992), which is based on the procedures outlined in Water Resource Council (WRC) Bulletin 17B (WRC 1981). The old Palisade gage (09106000), located upstream of the Grand Valley diversion, which has a period of record from 1902 to 1933, was used to evaluate the early period of record before the Cameo gage was installed in 1935. The suspended sediment sample record from 1982 to 1998 for the Cameo gage was retrieved from the USGS WATSTORE database, and analysis of the data was conducted to evaluate temporal trends in the suspended sediment concentrations.

2.2.2 Sedimentology

The sedimentologic characteristics of the Clifton site were determined by pebble counts (Wolman 1954) of the surface sediments, barrel samples of the surface and subsurface sediments (Milhous et al. 1995), freeze-core samples that encompassed surface muds, surface armor, and subarmor sediments (Milhous et al. 1995), and grab samples of the mud. The locations of the various samples are shown on Figures 2-3 and 2-6. The intent of the sampling was to quantify the surface and subsurface characteristics of the bed, bar and bank sediments within the site, as well as the overlying muds. Wolman pebble counts and freeze-core sampling were conducted at the Corn Lake site (Figure 2-4).

2.2.3 Topographic Surveys

A topographic and bathymetric survey of the entire Clifton site was completed in 1999 using a total station, and included the establishment of six permanently monumented cross sections and a survey control network for the site. All subsequent data collection at the site was tied to the established control network, thereby enabling all the data to be georeferenced. Survey-grade GPS provided by CDOW was used to tie the site into the State Plane Coordinate system. The cross sections and the site topography were used to develop both 1- and 2-D hydraulic models of the site. Throughout the period of study, water-surface elevations were surveyed at the site for the purpose of calibrating both 1- and 2-D hydraulic models. Water-surface elevations were measured for flows ranging from 500 to 11,300 cfs. The topography and bathymetry of the site and the locations of the monumented cross sections are shown on Figure 2-6.

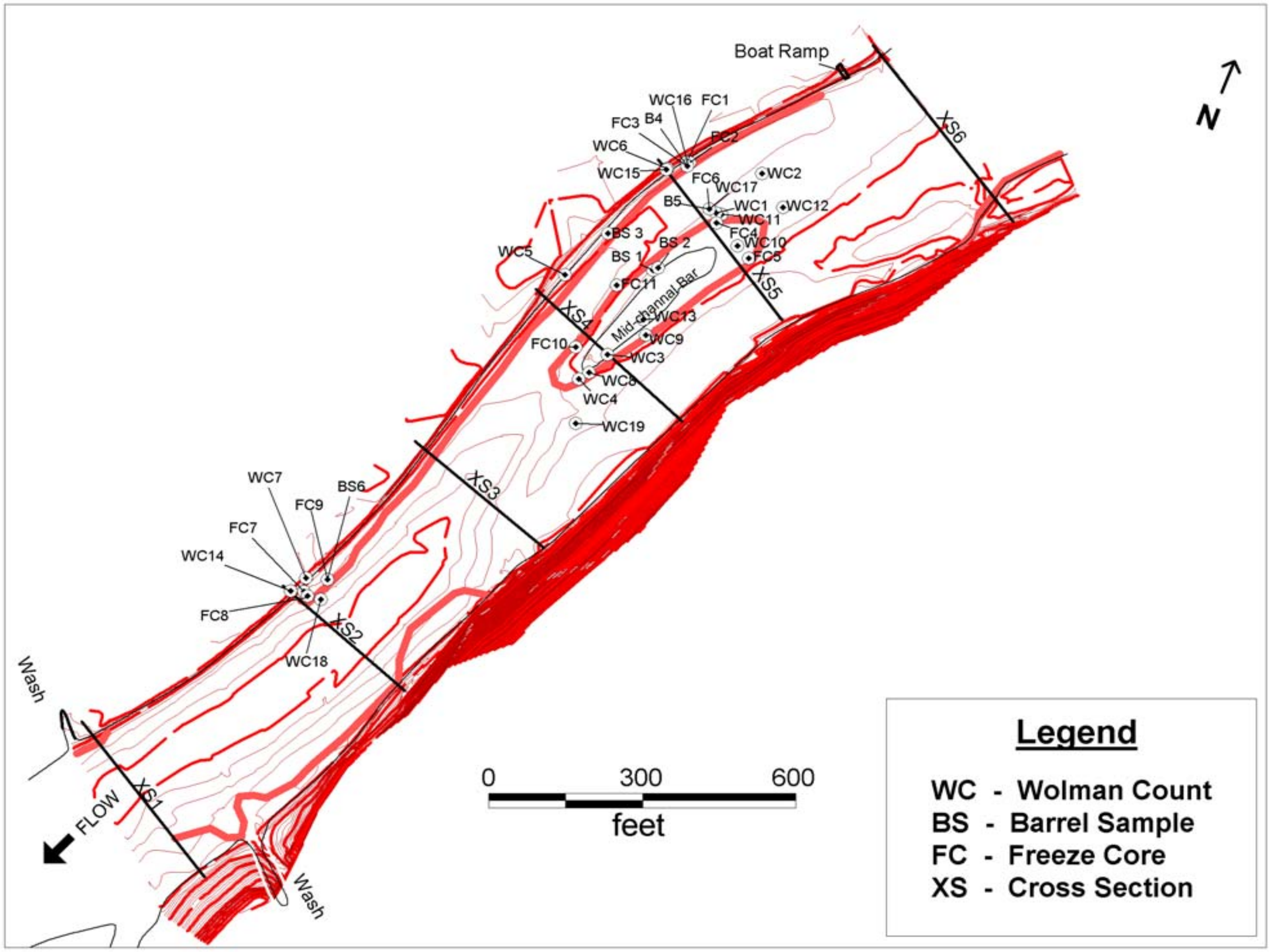


Figure 2-6. Map showing the locations of the various types of sediment samples at the Clifton site, as well as the site topography and bathymetry, and the monumented cross sections.

Topographic and bathymetric mapping of the Corn Lake site was conducted in 2000 by CDOW. The surveys were also tied into the State Plane Coordinate system with survey-grade GPS. MEI conducted supplemental topographic surveys in 2001 that were tied into the site control. The discharge in the river at the time of the survey by MEI was about 1,100 cfs. Site topography and bathymetry are shown on Figure 2-3. The topography and bathymetry were used to develop a 2-D hydraulic model of the site. Model calibration was based on the surveyed water-surface elevations at the time of the MEI survey, as well as measurements made by CDOW in 2000.

2.2.4 Automated Data Collection

A pumped sampler (ISCO Model 6700) and probes (YSI Model 6820, 6826) that measured turbidity, water temperature, river stage, water conductivity, and specific conductance (conductivity adjusted to a temperature of 25^{o}C)were installed on the right bank of the river just downstream of the Clifton Water Treatment Plant intake pump. Stored and real-time data were available from the site via telemetry. The sampler was initially installed in October 2000 for one month, and then was removed from the field. The sampler was reinstalled in spring 2001 prior to the commencement of the snowmelt runoff season. The sampler was programmed to retrieve one pumped sample per day over the course of the 2001, 2003 and 2003 snowmelt runoff seasons to provide a measure of the daily variation in suspended sediment concentration. Half-hourly turbidity, stage, water temperature, and conductivity measurements were also recorded for the entire period from spring 2001 to summer 2002. Following the snowmelt runoff season in 2001, the turbidity probe was programmed to trigger hourly-suspended sediment sampling during the post-runoff summer thunderstorm period when the turbidity exceeded a threshold value of 400 NTU. In 2002 and 2003, daily pumped samples were collected in the post-runoff period. Because of limitations imposed by the turbidity probe range, turbidity measurements are capped at 1,000 NTU, and therefore, mean daily values during the thunderstorm period when the suspended sediment loading can be expected to be highest, may underestimate the actual turbidity. Laboratory-determined NTU values for water samples recovered by the Clifton Water Treatment Plant have exceeded 10,000 NTU.

The pumped samples were delivered to Stewart Environmental Laboratories in Fort Collins for analysis. Due to a misunderstanding, the laboratory conducted total solids analysis of the samples rather than suspended-solids analysis. However, the concurrent measurement of specific conductance at the Clifton site enabled the suspended solids to be estimated from a relationship developed from the water-quality data collected between 1935 and 2000 by the USGS for the Cameo gage (No. 09095500). Figure 2-7 shows the inverse power function relationship between specific conductance (Y:microsiemens/cm) which is conductivity adjusted to a temperature of 25°C, and discharge (X:cfs)for the Cameo gage data ($R^2 = 0.93$):

$$Y = 89158X^{-0.58} \tag{1}$$

The specific conductance values are extremely high at low discharges because of the very high total dissolved solids in the water. This is the result of both geologic and man-induced factors in the lower elevation portions of the basin (Spahr et al. 2000). As a result, the effects of dissolved solids are proportionally higher during low-flow periods than during the high-flow periods. The annual dissolved solids load at the Cameo gage between 1973 and 1993 is estimated to be 1,500,000 tons (Spahr et al. 2000).

Figure 2-8 shows the linear relationship between dissolved solids (Y:mg/l)and specific conductance (X:microsiemens/cm) for the Cameo gage data for the same time period:

$$Y = 0.61X - 8.57 \tag{2}$$

The very strong relationship ($R^2 = 0.99$) derived from the Cameo gage data provides a solid basis for estimating the dissolved solid content of the samples retrieved by the automatic sampler, since the specific conductance at the time of sediment sampling is known. Subtraction of the estimated dissolved solids from the measured total solids provides an estimate of the suspended solids, and hence provides a means of estimating the suspended sediment concentration of the retrieved sample.

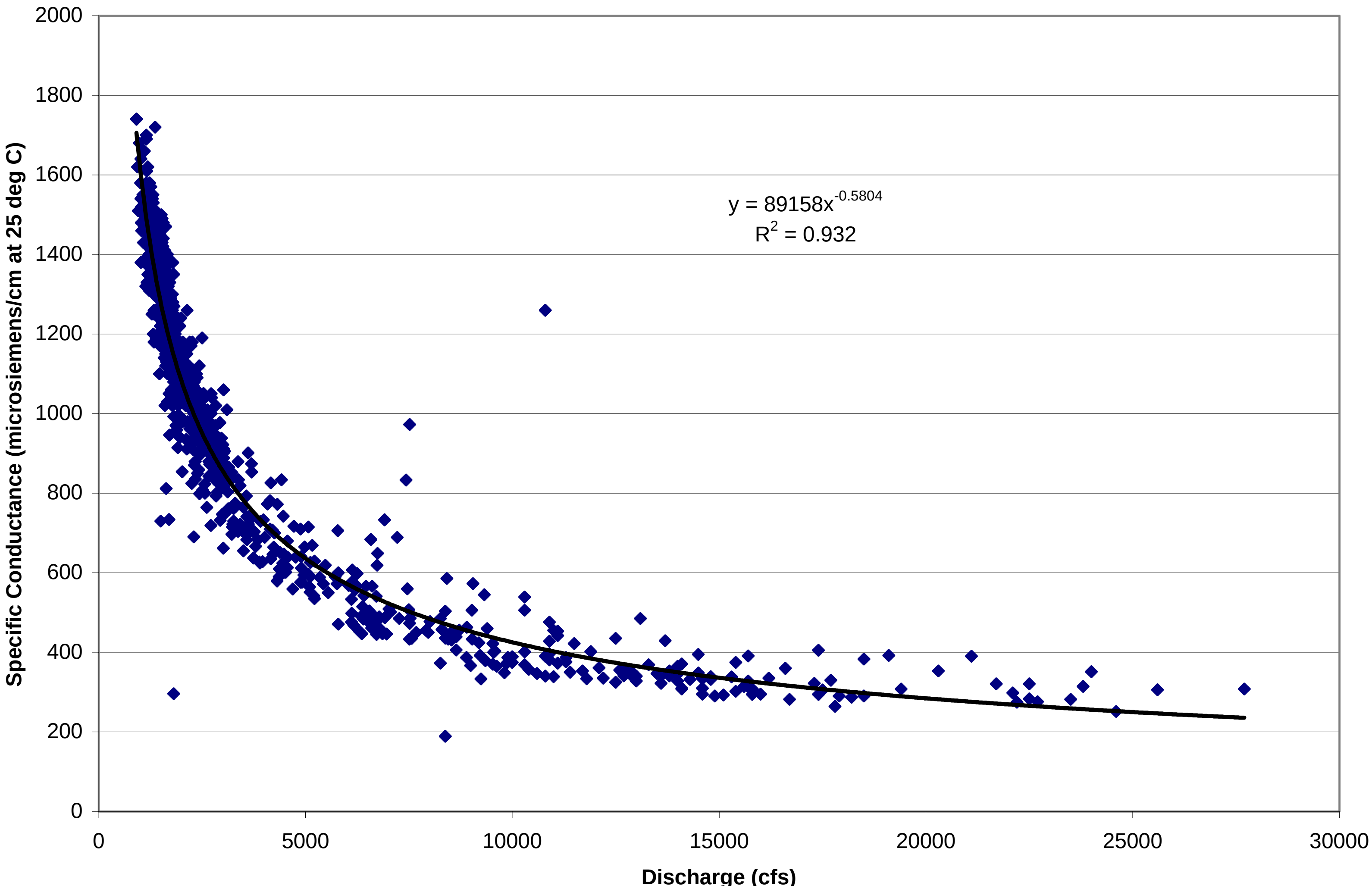


Figure 2-7. The relationship between discharge and specific conductance at the USGS Cameo gage between 1935 and 2000.

2.2.5 Mapping of Fine Sediment (Mud) Deposits at Clifton and Corn Lake Sites

On August 28 and 29, 2001, after there had been a number of thunderstorm runoff–induced elevated turbidity and suspended sediment concentration events, at a discharge at the Palisade gage of 1,030 cfs, the mud deposits at the Clifton site where the channel could be waded were physically mapped with a total station tied into the site control network. Observation of the site since the project commenced in 1999 indicated that regardless of the discharge, six "condition" zones with varying amounts of deposited mud on, and between, the gravels and cobbles that make up the channel-bed, bars and lower banks could be identified throughout the site. The locations of the spatial boundaries between the identified zones varied with discharge. Velocity data collected at the site in 2000 suggested that there was a threshold velocity for mud deposition in the range of 1 to 1.5 fps. If the velocity was greater than about 1.5 fps at any location throughout the site, there was very little evidence of mud deposition even if there was a high concentration of suspended sediments. Table 2-1 is the classification system used to map the site, and Figure 2-9 includes photographs of the individual classes.

The field boundaries between the various classes were determined by visual observation of the bed materials, and were recorded with the total station. Within the individual subaqueous mapping classes, 118 direct measurements of flow depth and mean column velocities were taken.

On August 30 and 31, 2001, 129 measurements of flow depth and velocity were made for the same classes (Table 2-1) at the Corn Lake site. No attempt was made to map the entire site, but as much of the site was waded as was possible.

Table 2-1. Classification used to map mud deposits at the Clifton site.

Class	Description
1	Subaerial thick mud deposits on channel and bar margins
2	Subaqueous thick mud deposits totally covering dead algae
3	Subaqueous mud deposits with some dead algae visible
4	Subaqueous mud with alive green algae
5	Dense algal growth with some mud trapped in the algae
6	Clean gravels and cobbles with no mud present

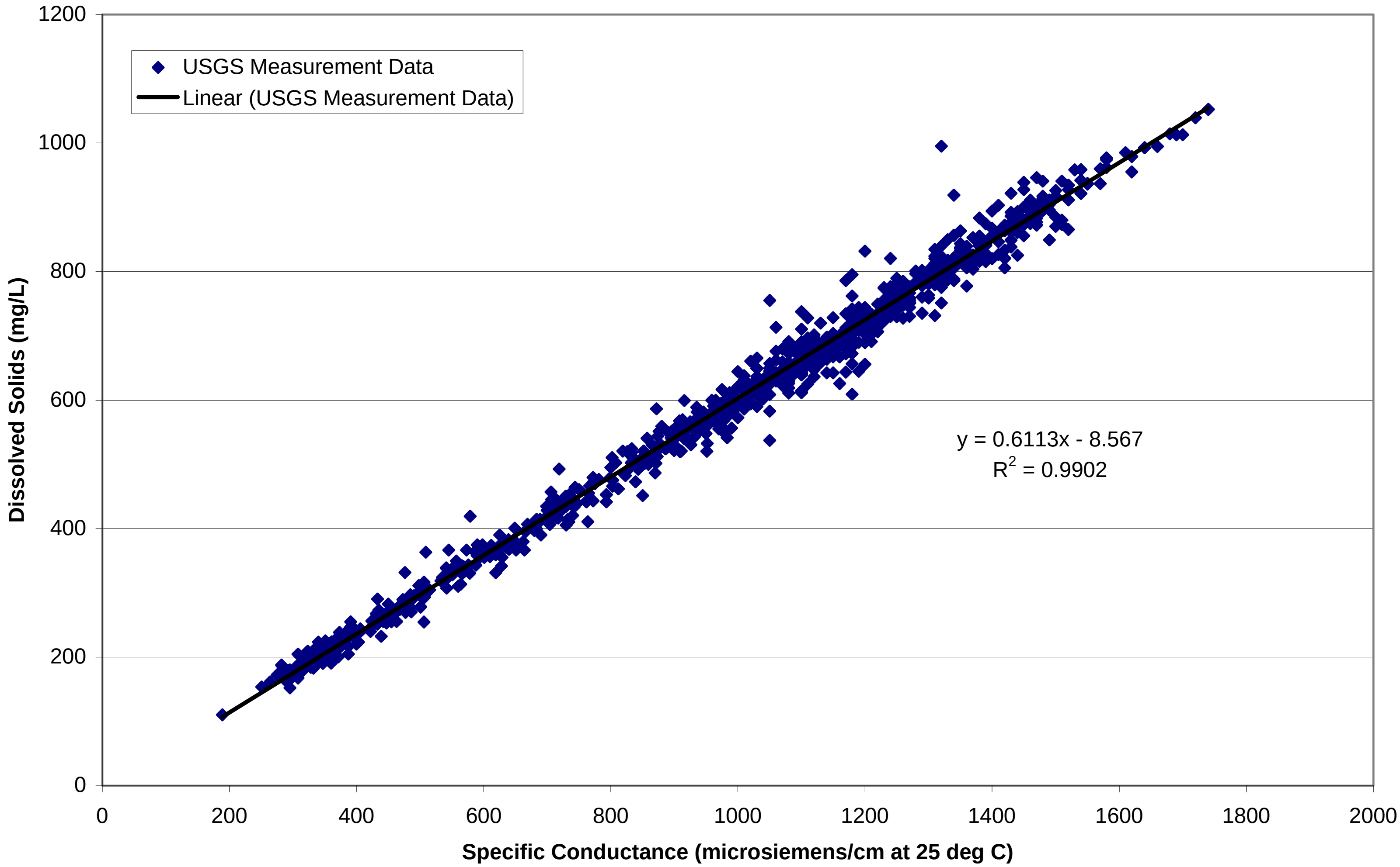


Figure 2-8. The relationship between specific conductance and dissolved solids at the Cameo gage between 1935 and 2000.

Figure 2-9. Photographs of the mud classes that were used to map the spatial distribution of the mud deposits at the Clifton and Corn Lake sites in the 15-MR.

2.2.6 Tracer Investigation

To address the question of re-entrainment of previously deposited mud, tracers were injected into existing mud deposits at the head of the mid-channel bar at the Clifton site on October 16, 2001, when the discharge in the river was 830 cfs. Based on the results of USGS chemical characterization of bottom sediments from upstream of the Price-Stubb Diversion dam (USGS 2000), silver nitrate ($AgN0_3$) and nickel chloride ($NiCl_2$) were used as tracers to investigate the permanence or transience of the mud deposits. Ten locations at the head of the mid-channel bar were injected, half with 10 percent solutions of silver nitrate, and half with 20 percent solutions of nickel chloride, in fall 2001. A drilled template (8x10 in) with holes spaced on 0.5-inch centers was placed on the selected mud deposits, the center of the template was surveyed in with a total station, and 4 ml of solutions were injected into 50 holes in the mud deposits with a hypodermic syringe. Figure 2-10 shows the locations of the injection sites, and Figure 2-11 shows the mud surface at Site 6, and the thickness of the mud deposit, respectively. Four samples were collected from mud deposits that had not been injected to determine background levels of the 2 metals at the time of the initial injection of the tracers. Mud from the injected sites was resampled on April 9, 2002, prior to the onset of the snowmelt runoff season to determine whether the metals may have leached out of the mud deposits since they were injected in October. The injected mud sites were resampled on June 27, 2002, after the snowmelt runoff to determine if the mud deposits had been remobilized by the higher flows during the runoff period. Following the sampling in April and June the samples were analyzed for the two tracer metals.

2.2.7 Numerical Modeling

Using the surveyed site topography, one-dimensional (1-D) and two-dimensional (2-D) hydraulic models were developed for the Clifton site. The 1-D HEC-RAS (COE 2001) computer model was developed to provide boundary conditions for the 2-D RMA-2V computer model. A split-flow 1-D model was developed because two separate flow paths are present until the mid-channel bar is submerged at a discharge of about 4,800 cfs. Although the 1-D model will provide adequate hydraulic information to conduct incipient motion and other sediment-transport

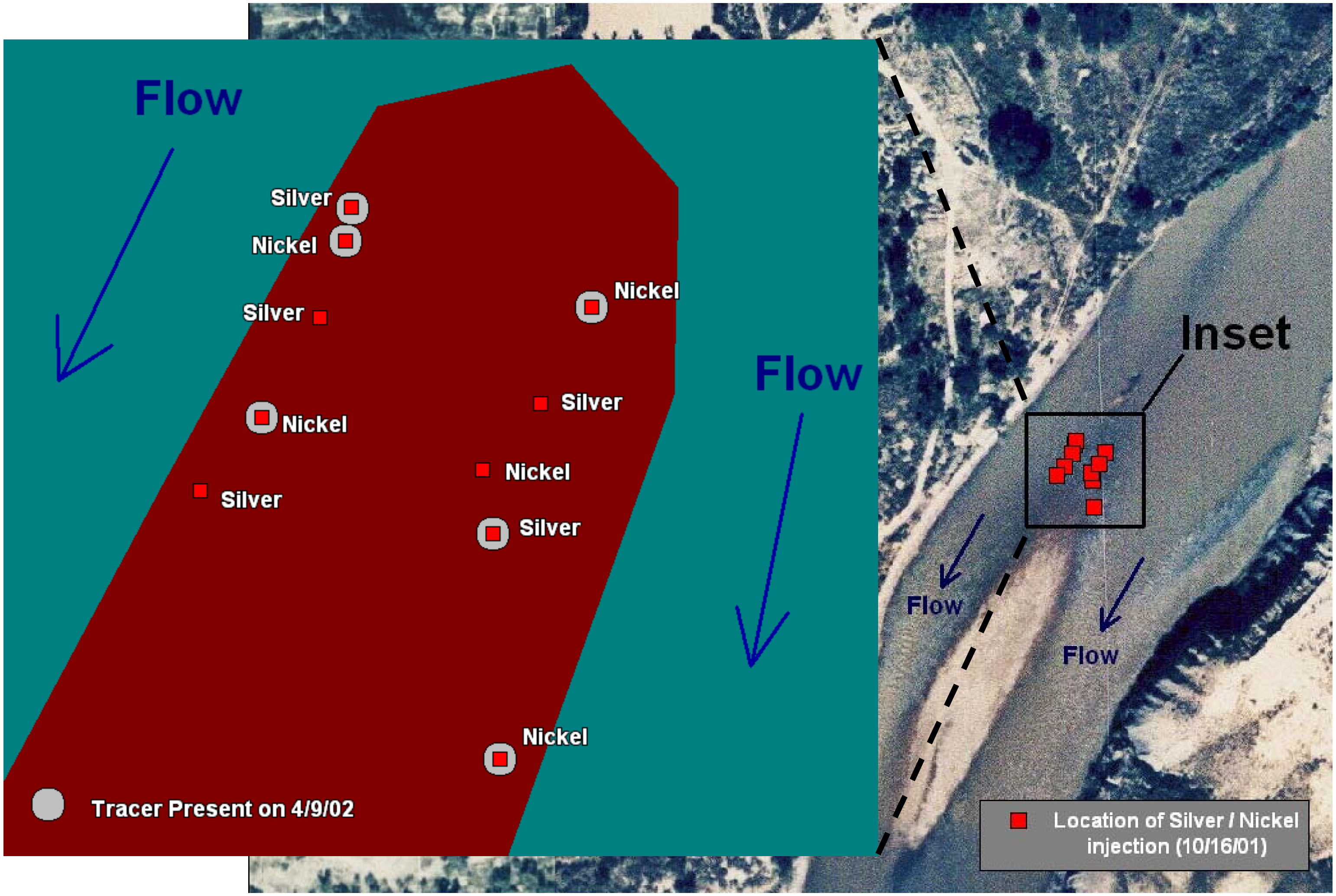


Figure 2-10. Map showing locations of the nickel chloride and silver nitrate injection sites at Clifton.

Figure 2-11. Photographs of the mud surface at Site 6 and the thickness of the mud that overlies the gravels and cobbles. The scale is 4 in (10cm) long.

analyses, the 2-D model output is preferable when evaluating meso- and microscale habitats (Mussetter et al. 2001). The 2-D hydrodynamic model of the reach was created from the mapped topography using the BOSS SMS software. SMS acts as a graphical interface for the U.S. Army Corps of Engineers RMA2V (Version 4.3) (1997) model, a finite-element hydrodynamic numerical model that computes depth, velocity and direction of flow at nodes within a mesh that represents the site. The models were calibrated to measured water- surface elevations for a range of discharges between 500 and 11,300 cfs. Figure 2-12 shows the calibration of the HEC-RAS model at a discharge of 2,000 cfs. The 2-D model was run with discharges of 800, 1,100, 1,400, 2,000, 4,800, 8,000, 11,340, 13,000, 15,000, 20,000, and 25,000 cfs to encompass the potential range of flows that might be involved in sediment mobilization and transport.

2.2.8 Analysis of Bed Material Mobilization

Incipient motion analysis for the bed material at the Clifton site was conducted with output from the 2-D model by evaluating the effective shear stress on the channel bed in relation to the amount of shear stress that is required to move the sediment sizes that are present. This was accomplished by computing the normalized grain shear stress (ϕ'), which is the ratio of the grain shear stress (τ') to the critical shear stress for particle mobilization (τ_c), or:

$$\phi' = \frac{\tau'}{\tau_c} \tag{3}$$

Grain shear stress (τ') was used in the calculations rather than the total shear stress because grain shear stress is a better representation of the near-bed hydraulic forces acting on the individual sediment particles on the bed. Total shear stress overestimates the forces that are available to mobilize sediment because it includes the effects of form roughness associated with irregularities in the channel bed and banks, and other obstructions such as vegetation that reduce and dissipate energy in the flow (Mussetter et al. 2001; Harvey et al. 1993).

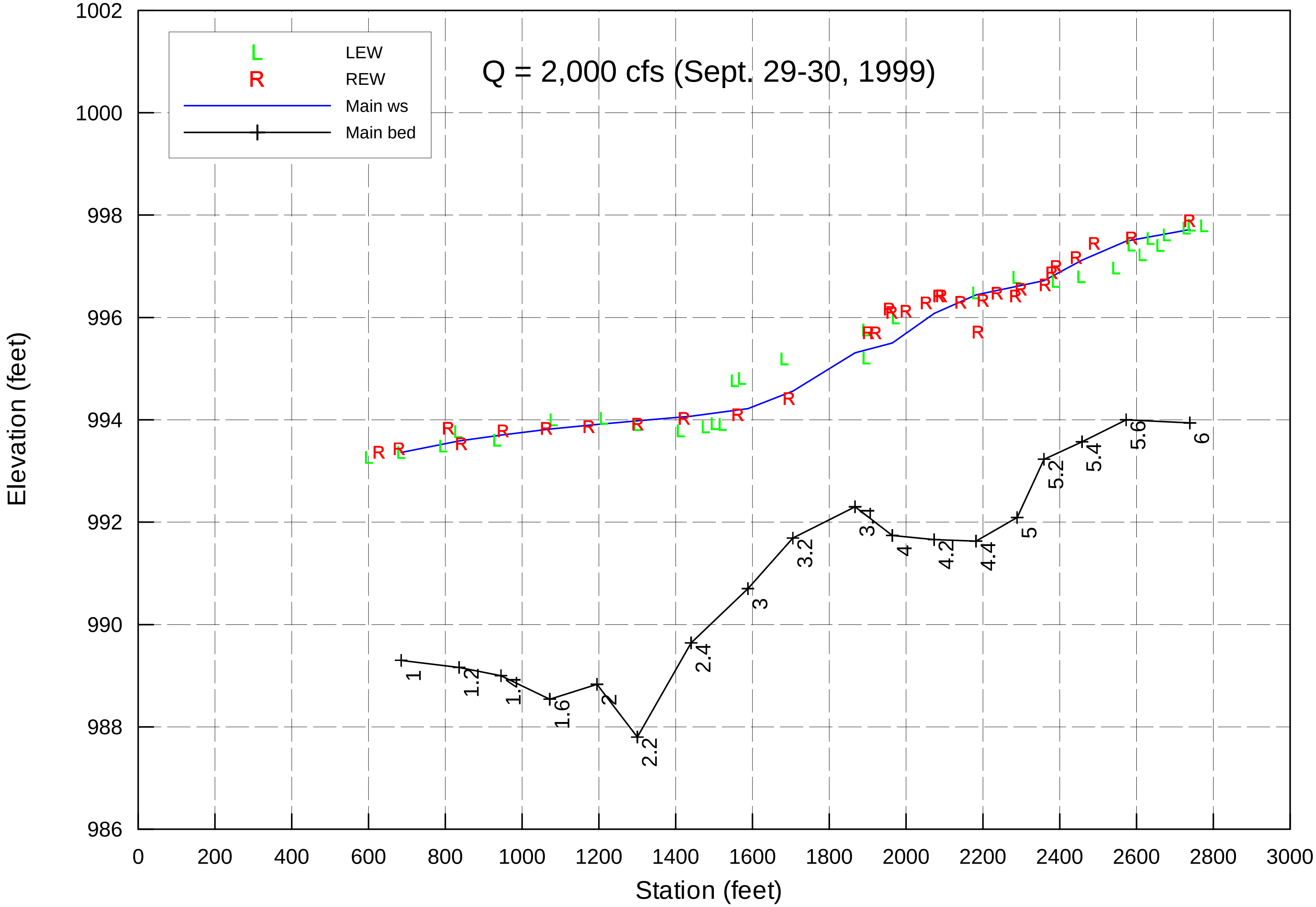


Figure 2-12. Bed profile and a 2,000-cfs water-surface profile developed from the HEC-RAS model of the Clifton site. Measured water-surface elevations along the reach at 2,000 cfs are also shown.

Grain shear stress is computed from the following relationship:

$$\tau' = \gamma Y'S \tag{4}$$

where Y' is the portion of the total hydraulic depth associated with grain resistance (Einstein, 1950) and S is the energy slope at the cross section.

The value for S is obtained from a solution of the Manning's Equation:

$$S = \left(\frac{nV}{1.49\,(Y')^{2/3}}\right)^2 \tag{5}$$

where the Manning's *n* roughness value comes from the SMS output. The roughness value varies spatially and with flow depth in the Clifton reach model. A curve of depth versus roughness was generated for each material type based on four coefficients: RDR0, RDD0, RDRM, and RDCOEF (COE 1997). Roughness is calculated using the following equation:

$$n = \left(\frac{RDR0}{D^{RDCOEF}}\right) + \left(RDRM * EXP(-D / RDD0)\right) \tag{6}$$

where RDR0 is the maximum Manning's *n*-value for non-vegetated water, RDD0 is the depth at which vegetation effects roughness, RDRM is the Manning's *n*-value for vegetated water, RDCOEF is a roughness by depth coefficient, and D is depth from the SMS model output.

The value of Y' is computed by iteratively solving the semilogarithmic velocity profile equation:

$$\frac{V}{V_*'} = 6.25 + 5.75\,log\left(\frac{Y'}{k_s}\right) \tag{7}$$

where V is the mean velocity at the cross section, k_s is the characteristic roughness of the bed, and V_*' is the shear velocity due to grain resistance, given by:

$$V_*' = \sqrt{gY'S} \tag{8}$$

The characteristic roughness height of the bed (k_s) is approximately 3.5 D_{84} (Hey 1979).

Critical shear stress (τ_c) is estimated using the Shields (1936) relation, given by:

$$\tau_c = \tau_{*_c}(\gamma_s - \gamma) D_{50} \tag{9}$$

where τ_{*c} is the dimensionless critical shear stress (often referred to as the Shields parameter), γ_s is the unit weight of sediment (~165lb/ft^3), γ is the unit weigh of water (62.4 lb/ft^3), and D_{50} is the median particle size of the bed material. In gravel and cobble bed streams, when the critical shear stress for the median (D_{50}) particle size is exceeded, the bed is mobilized and all sizes up to about five times the median size are capable of being transported by the flow (Parker et al. 1982; Andrews 1984). At lower shear stresses, the bed is effectively immobile.

Reported values for the critical Shields parameter (τ_{*c}) range from 0.03 (Neill 1968; Andrews 1984) to 0.06 (Shields 1936). A value of 0.047 is commonly used in engineering practice, based on the point at which the Meyer-Peter, Müller bed-load equation indicates no transport (Meyer-Peter and Müller 1948). Detailed evaluation of Meyer-Peter and Muller's data, and more recent data (Parker et al. 1982; Andrews 1984), indicate that a value of 0.03 is more reasonable for true incipient motion in gravel- and cobble-bed streams. In fact, Neill (1968) concluded that a dimensionless shear value of 0.03 corresponds to true incipient motion of the bed material matrix while 0.047 corresponds to a low, but measurable transport rate. For this study, a critical Shields value of 0.03 was used to represent incipient conditions.

Considering Neill's (1968) observations, when the normalized shear stress (ϕ') is approximately 1, the bed begins to mobilize, and substantial transport of the bed material occurs when it exceeds about 1.5. The computational procedure thus provides a convenient means of evaluating conditions for gravel mobilization within the Clifton reach. Based on the measured bed material gradations through the reach, a representative surface gradation was developed which had a median (D_{50}) size of 81 mm and a D_{84} of 125 mm.

2.3 Biological Methods

The biological portion of this joint investigation monitored biotic community characteristics at riffle-run habitat units before and after the peak runoff. The biological parameters primarily included periphyton and benthic macroinvertebrate sampling. Small-bodied fish were also sampled on one occasion. Figure 2-13 summarizes the trophic relationships between biotic groups in the 15-MR. Periphyton and benthic macroinvertebrates are two components that can be used as indicators of primary and secondary productivity and form the basic foodweb components for Colorado pikeminnow prey. It is hypothesized that increases in productivity levels (mainly through increased productivity in run habitats) can lead to increases in population numbers for species at higher trophic levels (Osmundson 1999). It is intended that the biological component of this study be used in conjunction with the physical responses to flow regime to project limitations to higher trophic levels in the 15-MR of the Colorado River.

2.3.1 Macroinvertebrate and Periphyton Sampling

Macroinvertebrate and periphyton sampling were conducted at the same location on each sampling date at the Clifton site (Table 2-2). Three replicates were taken from each habitat on each sampling occasion. Efforts were made to establish sampling locations that reflected effects of the peak flow, and other natural events and minimized localized influences. A total of 90 samples were taken for each biological component at each site during the study period. Additional periphyton and macroinvertebrate samples were taken as part of the synoptic study during 2001 (Table 2-3).

A Secchi disk was used as a surrogate evaluation for turbidity measurements on each sampling occasion at each site. From the year 2000 to 2003 sampling season, the total depth and mean current velocity were measured at each specific sampling location for comparison among habitat types. Velocity was measured at 0.6 of total depth with a Swoffer Model 2100 velocity meter and topset rod.

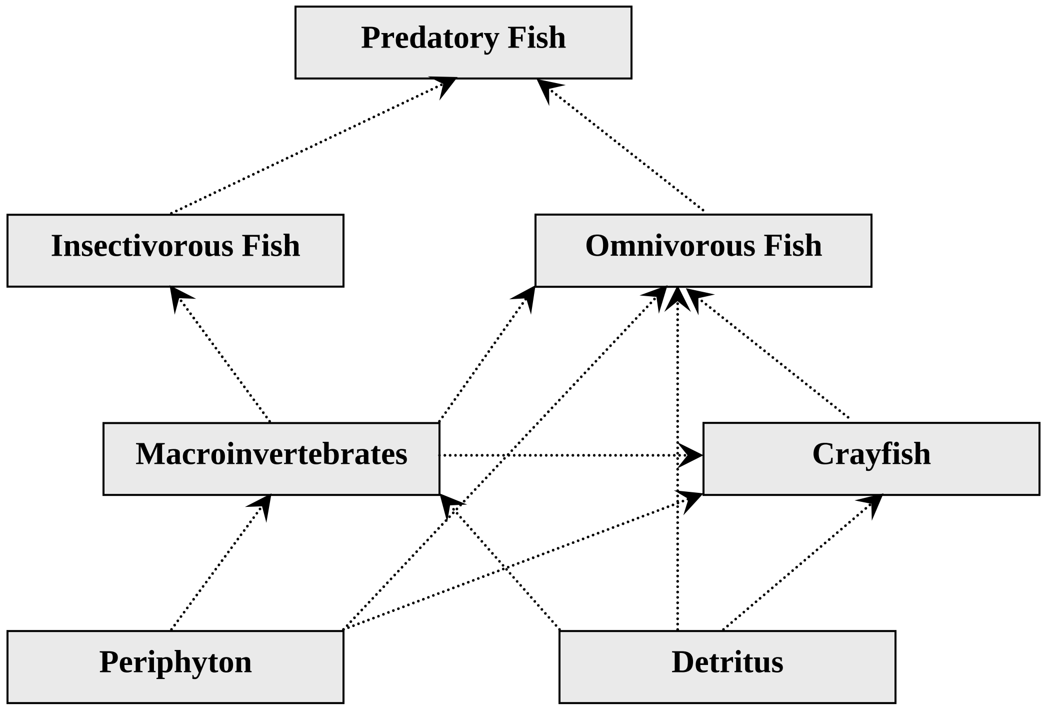


Figure 2-13. A summary of trophic relationships (energy flow) that occur in the 15-MR of the Colorado River.

Table 2-2. Sample dates and number of replicates taken at the Clifton site, Colorado River, Colorado.

	CLIFTON		CLIFTON	
	Periphyton		Macroinvertebrates	
	Site 5	Site 2	Site 5	Site 2
	Riffle	Run	Riffle	Run
19 May 99	3	3	3	3
9 Jun. 99	3	3	3	3
13 Jul. 99	3	3	3	3
19 Aug. 99	3	3	3	3
16 Sep. 99	3	3	3	3
27 Oct. 99	3	3	3	3
7 Jun. 00	3	3	3	3
12 Jul. 00	3	3	3	3
7 Aug. 00	3	3	3	3
16 Aug. 00	3	3	3	3
29 Aug. 00	3	3	3	3
12 Sep. 00	3	3	3	3
16 Oct. 00	3	3	3	3
17 May 01	3	3	3	3
12 Jun. 01	3	3	3	3
12 Jul. 01	3	3	3	3
16 Aug. 01	3	3	3	3
28 Aug. 01	3	3	3	3
10 Sep. 01	3	3	3	3
18 Oct. 01	3	3	3	3
27 Jun. 02	3	3	3	3
19 Jul. 02	3	3	3	3
16 Aug. 02	3	3	3	3
16 Sep. 02	3	3	3	3
16 Oct. 02	3	3	3	3
16 Jul. 03	3	3	3	3
13 Aug. 03	3	3	3	3
3 Sep. 03	3	3	3	3
16 Sep. 03	3	3	3	3
21 Oct. 03	3	3	3	3
Total	**90**	**90**	**90**	**90**

Table 2-3. Sample dates and number of replicates taken at the synoptic sites, Colorado and Gunnison rivers, Colorado.

			17 May 01	28 Aug. 01	18 Oct. 01
UP	Periphyton	Riffle	3	3	3
		Run		3	3
	Macroinvertebrate	Riffle	3	3	3
		Run		3	3
M-46	Periphyton	Riffle			
		Run			
	Macroinvertebrate	Riffle		3	
		Run			
CL	Periphyton	Riffle		3	3
		Run		3	3
	Macroinvertebrate	Riffle		3	3
		Run		3	3
LO	Periphyton	Riffle	3	3	3
		Run		3	3
	Macroinvertebrate	Riffle	3	3	3
		Run		3	3
FB	Periphyton	Riffle	3	3	3
		Run		3	3
	Macroinvertebrate	Riffle	3	3	3
		Run		3	3
LOF	Periphyton	Riffle	3	3	3
		Run		3	3
	Macroinvertebrate	Riffle	3	3	3
		Run		3	3
GUN-Esc	Periphyton	Riffle		3	3
		Run		3	3
	Macroinvertebrate	Riffle		3	3
		Run		3	3
Total	**Periphyton**		**12**	**36**	**36**
	Macroinvertebrate		**12**	**39**	**36**

2.3.1.1 Periphyton

Periphyton (algae) samples were collected monthly throughout each sampling season from large cobble substrate at each site. Large cobble substrate was common in both habitats (see Figures 3-11 and 3-12). Samples were collected from unshaded areas of similar depth to minimize the variability that might be caused by light penetration. A single smooth stone (cobble size) was randomly selected and a known surface area was scraped to obtain quantifiable periphyton data. Three replicate samples were collected at each site. These samples were preserved in a 10% formalin solution, returned to the lab, and identified to the lowest practical taxonomic level.

Several indices (metrics) were employed to assist in the evaluation of the periphyton samples. Shannon-Weaver diversity (diversity), population density (density), and species richness were calculated for each site on each sampling occasion. These metrics are described in greater detail in the macroinvertebrate section. Biovolume was also calculated for each site beginning with samples taken during the year 2000. Biovolume is often used as an indication of periphyton productivity. The combined indices were used to determine trends in algal growth, standing crop and production.

2.3.1.2 Macroinvertebrates

Macroinvertebrate samples were collected monthly starting as early as May and always running through October (with multiple sampling often occurring in August or September). At each site three samples were taken using a Hess Sampler with 500 μm mesh in order to provide quantitative macroinvertebrate data. All samples were taken in areas of similar size substrate and similar depth to avoid bias that may be associated with these variables. Depth at each sample location ranged between 24.4 cm and 33.5 cm. Substrate within the Hess Sampler was thoroughly disturbed and individual rocks were scrubbed by hand to dislodge all benthic organisms. Any fish or crayfish that were collected were released back into the river. Although crayfish may be an important macroinvertebrate food source for fish in this system, the sampling technique used in this study was not adequate for measuring crayfish populations. All other macroinvertebrates were preserved in 70% ethanol and transported to the lab where they were sorted, enumerated and identified to the lowest practical taxonomic level (Merritt and Cummins 1996; Ward et al. 2002). Detritus from each Hess sample was dried in an oven at 100°C until all water content had evaporated. Detritus was then weighed to provide quantitative dry weights of organic material. Macroinvertebrate population densities and species lists were developed for each site on each sampling occasion. Data collected were used in various indices to provide information regarding aquatic conditions. The following indices were used in this study.

Shannon-Weaver diversity and evenness (evenness) values were used to detect changes in macroinvertebrate community structure. In pristine waters, diversity values typically range from near 3.0 to 4.0. In polluted waters this value is generally less than 1.0. The overall evenness value ranges between 0.0 and 1.0, with values lower than 0.3 indicative of organic pollution

(Ward et al. 2002). Diversity and evenness are similar measurements because they both rely heavily on the distribution of taxa that are collected, although species richness also influences diversity. Both indices are designed to detect unbalance in communities where a few species are represented by a large numbers of individuals. These situations are usually the result of pollution-induced changes to the aquatic community. Diversity and Evenness were used in this study as a surrogate for water quality monitoring. They are not necessarily sensitive indicators of sediment related problems; however, some sediment-induced changes related to drift rate or microhabitat availability might influence these values.

The Hilsenhoff Family Biotic Index (FBI) is another metric that was used to measure balance in macroinvertebrate community structure. Its primary value lies in detecting organic pollution because it is derived from the proportion of taxa, and their assigned tolerance values, based on their sensitivity to organic pollution (Plafkin et al. 1989). Because the structure of macroinvertebrate communities changes in different regions, the number indicating a certain water quality rating for organic pollution will vary among rivers. A comparison of the values produced within a given system provides information regarding the location and sources of impact from organic pollution. Values for the FBI range from 0.0 to 10.0. Lower FBI values indicate better water quality.

The Ephemeroptera, Plecoptera, Trichoptera (EPT) index was also employed to assist in the analysis of data. It is a direct measure of taxa richness among species that are generally considered to be sensitive to disturbances (Plafkin et al. 1989). Most invertebrate species have specific habitat requirements. The value produced by this metric indicates preferred habitat types as well as disturbance or modification of habitat. This value could also reflect changes in location if the change in location results in different physical habitat features. The EPT index is reported as the total number of distinguishable taxa in the orders Ephemeroptera, Plecoptera and Trichoptera found at each site. Results provided by this metric will naturally vary among river systems, but are valuable when comparing samples taken during different years from the same reach. The EPT index was used in analysis of this data to determine habitat preference and monitor disturbance sensitive species.

Taxa richness was also reported for each sampling event during the study. This measurement is simply reported as the total number of identifiable taxa collected on each date from each sampling location. It is similar to the EPT index, except that it includes all aquatic macroinvertebrate species. Taxa richness is useful when describing differences in habitat complexity or aquatic conditions between rivers or site locations. Taxa richness may also provide some indication of habitat preference and microhabitat heterogeneity.

Macroinvertebrate standing crop at each site was determined using density and biomass. Macroinvertebrate density was reported as the mean number of macroinvertebrates/m^2 found at each location. Densities were compared between sites for each sampling occasion. Biomass was reported as the mean dry weight of macroinvertebrates/m^2 at each site location. These values were obtained by drying macroinvertebrates from each sample in an oven at 100° C for 24-hours or until all water content had evaporated (no decrease in weight could be detected). Biomass values provide production related information in terms of weight of macroinvertebrates produced by each habitat. Density and biomass provide a means of measuring and comparing standing crop and provide an indication of productivity at each sampling location.

The final measurement used in this study was an analysis of macroinvertebrate functional feeding groups. This process provides a measurement of macroinvertebrate community function as opposed to other metrics that measure community structure. Aquatic macroinvertebrates were categorized according to feeding strategy to determine the relative proportion of various groups. Species were placed into functional feeding groups based on acquisition of nutritional resources (Merritt and Cummins 1996; Ward et al. 2002). The proportion of certain functional feeding groups in the macroinvertebrate community can provide insight to various types of stress in river systems (Ward et al. 2002). River ecosystems that provide a variety of feeding opportunities usually maintain good representation of each corresponding functional feeding group. Numerous variables (including habitat quality) may affect the proportions of certain functional feeding groups.

2.3.1.3 Statistical Analysis

All of the indices used to evaluate periphyton and macroinvertebrate data fall into one of two categories based on statistical analysis. Some of the indices are calculated using data that were pooled from all three replicates. These indices include diversity, evenness, FBI, EPT, and functional feeding groups. Pooled data have no mean or standard error associated with a particular sampling event. The other indices (taxa richness, density, biomass, and biovolume) are calculated for each replicate, and therefore, have associated means and standard errors. These metrics were most useful in the statistical analysis.

Descriptive statistics were generated for total insect density, total insect biomass, insect taxa richness, periphyton taxa richness, and total periphyton density. Means (and 1 standard error) were plotted to investigate differences among years and differences between riffle and run communities for these responses.

Multiple linear regression models were developed separately, using the SAS statistical package (SAS 1996), for riffle and run habitat data to determine which hydrologic and sediment-related (e.g. turbidity) variables influenced biological community responses. The biological responses that were tested included total insect density, insect taxa richness, insect biomass, periphyton biovolume, periphyton density, and periphyton richness. The multiple regression approach identified the relative importance of the variables that were tested. The relative importance of each variable could not have been determined if each variable was tested separately. Individual samples were considered sub-replicates since hydrologic and turbidity data were not specific to each sample (except velocity). Therefore, data from these samples were averaged for each date for a final sample size of 31 dates. Several independent variables were highly correlated (Pearsons Product - Moment Correlation: $r>0.9$ and $P<0.0001$) and thus were removed from regression models to reduce variance inflation due to high collinearity. Average daily turbidity was removed but was still of interest, so Pearson correlation coefficients were generated between this variable and community response variables to determine direction and strength of relationships. Velocity was not included in regression models as an independent variable since there were no values for 1999. It is also important to note that sample size was reduced for periphyton biomass (not collected in 1999). The following variables were left in initial regression models: annual peak flow, average daily discharge, number of days below base turbidity (50 NTU), percent change in turbidity, the number of days above a turbidity threshold of 400 NTU, and two-way interactions. The percent change in turbidity was calculated using the following equation.

Percent change in NTU since last sample = ((A-B)/C) x 100

Where A = the mean turbidity from the 14 days prior to sampling

B = the mean turbidity from the 14 days prior to those days used to calculate A, and

C = the mean turbidity from A and B.

These independent variables were transformed (natural or power 10 logarithm, squareroot, arcsine, inverse, or a combination) as needed to approximate a normal distribution. Their relative importance to community responses were compared with two types of model selection; stepwise selection and selection based on adjusted R-squared plus AIC values. These model selection techniques determine which variables (and interactions of variables) best explain variation in community responses. The final best model was determined by comparing results of the model selection techniques, and this model was run to determine parameter estimates (mean and SE) and significance levels of each parameter. Model assumptions (normality and hetereoscedasticity of errors) and potential problems with influential outliers and collinearity were checked with diagnostic tests available in SAS.

2.3.1.4 Fish Populations

Fish population estimates for riffle and near-shore run habitats were made using an electrofishing technique during late August base flows. Sufficient population closure was achieved by the use of block nets at the downstream site terminus and block nets set perpendicular to the downstream net. When possible, the shoreline was used as a natural barrier on one side. This three sided enclosed section was shocked in a downstream manner using a multiple electrode barge electroshocker with a Smith-Root 5.0 GPP and a 5 kilowatt generator. A three pass removal method was used to determine population estimates for all habitats sampled. All fish captured during each electrofishing pass were removed and placed in holding nets until all passes were completed. Data recorded for individual fish were: species, total length (mm), standard length (mm), weight (g), and any general relevant information (i.e. presence of external parasites, reproductive status, sex, morphological information). Data was entered into a spreadsheet program and fish larger than 150 mm (total length) were removed from the analysis. Population estimates were determined using the computer program MicroFish version 3.0 (Van Deventer and Platts 1989).

3 RESULTS

This chapter presents the results of the physical process and biological investigations that were conducted for this investigation.

3.1 Physical Processes

The results of the various components of the physical processes investigation are presented in the same order as the methods in Chapter 2.

3.1.1 Hydrology

To place the period of record of data collection at the Clifton and Corn Lake sites in perspective, and to evaluate the historic changes in the hydrology of the 15-MR, a review of the hydrologic and sediment records at the USGS Cameo (09095500), and Palisade (old site, 09106000) and Palisade (new site, 09106150) gages was conducted. Previous investigations indicate that there has been about a 30 percent reduction in the annual peak discharges at the Cameo gage on the Colorado River since 1950 (Pitlick and Van Steeter 1994; Pitlick et al. 1997; Van Steeter and Pitlick 1998; Pitlick and Van Steeter 1998; Pitlick et al. 1999; Pitlick and Cress 2000). The peak flow-frequency curve for the period from 1902 to 1933 (old Palisade gage) shows the 2-year peak discharge was on the order of 32,000 cfs, and the 5-year peak was about 42,000 cfs (Figure 3-1). The peak flow-frequency curve for the Cameo gage for the period between 1950 and 2000 shows the 2-year peak discharge is about 18,000 cfs, and the 5-year is about 24,000 cfs (Figure 3-2). Comparison of the magnitudes of the 2- and 5-year frequencies indicates that there has been about a 40 percent reduction in the peak discharges. The peak flow record for the new Palisade gage is too short (1990 to 2003) to develop a flood-frequency curve. The old Palisade and Cameo gage data do, however, indicate that there has been a significant reduction in the peak-flow regime for the 15-MR, and the differences in the reported magnitude of the change (Pitlick et al. 1997) is due to differences in the method of computation.

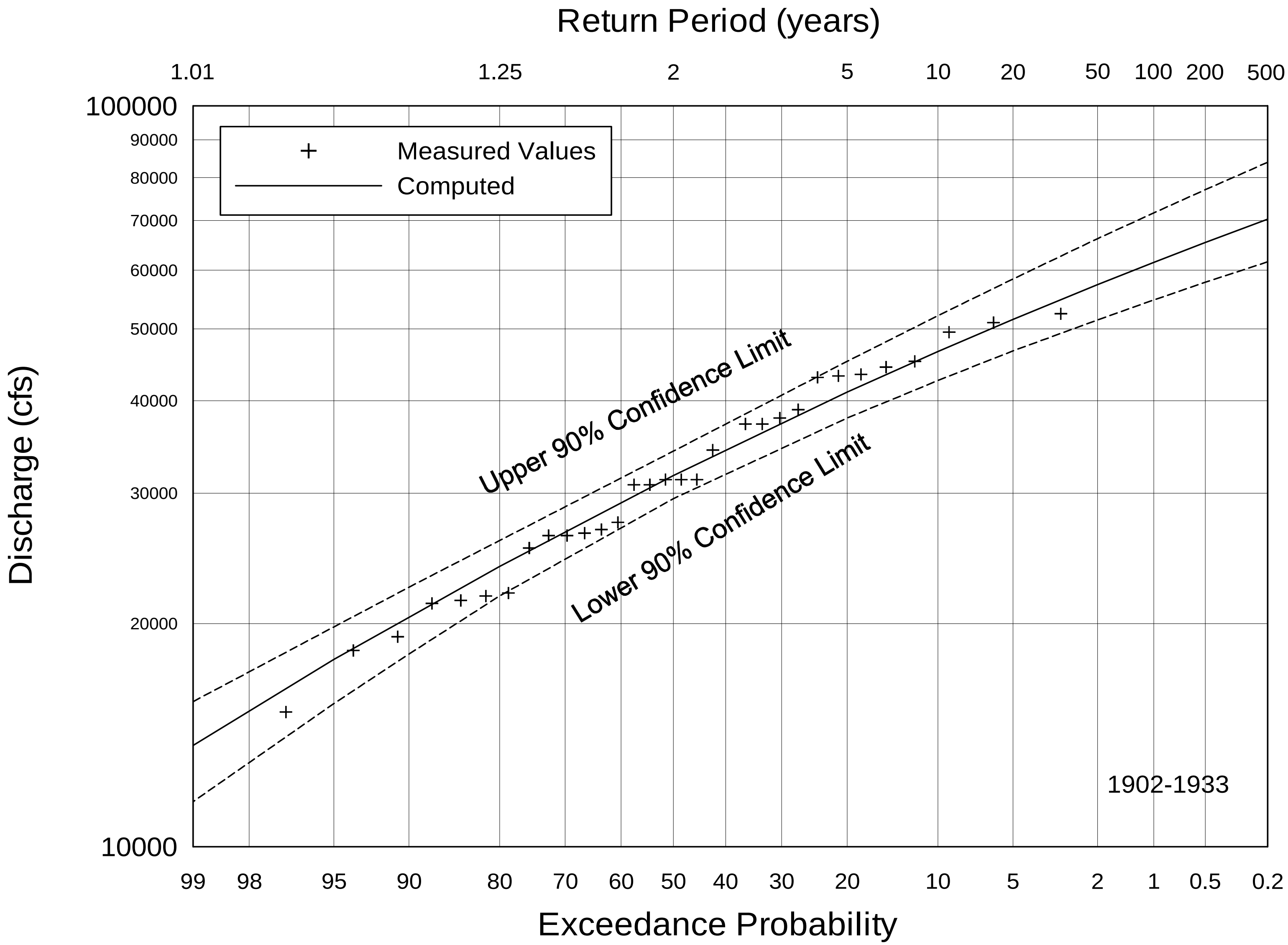


Figure 3-1. Peak flow-frequency curve for Colorado River at the old Palisade gage (09106000) for the period between 1902 and 1933.

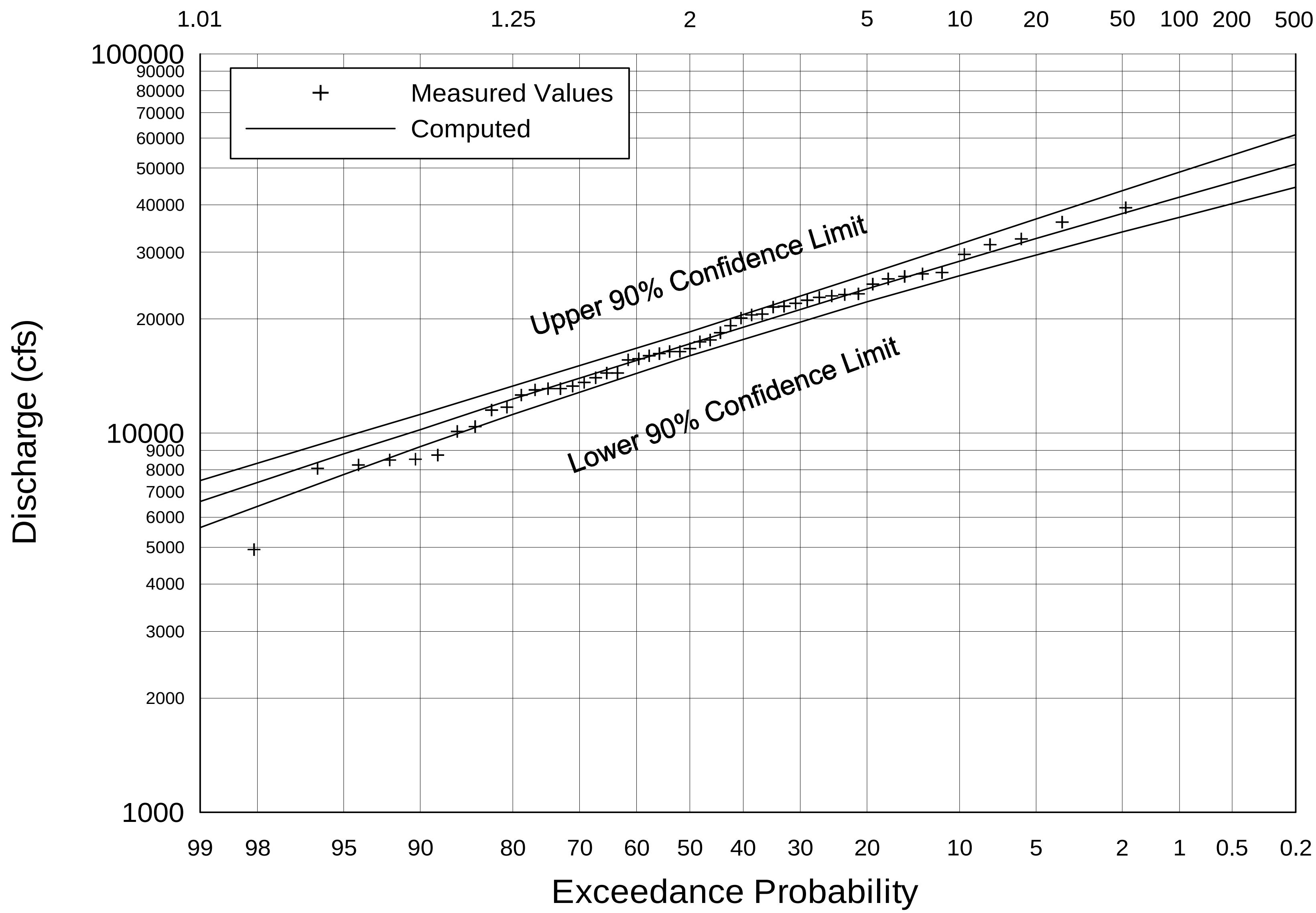


Figure 3-2. Peak flow-frequency curve for Colorado River at the Cameo gage (09095500) for the period between 1950 and 2000.

During the period of data collection (1999-2003) in the 15-MR, most of the years have not approximated the average annual hydrograph. The peak discharge in WY 1999 exceeded the average peak and this water year is the closest to approximating the average annual hydrograph of all years during the study (Figure 3-3). The peak discharge in WY 2000 exceeded the average (12,000 cfs), but the duration of the snowmelt runoff event was about one month shorter than the average (Figure 3-4). In WY 2001, the peak discharge (8,100 cfs) was considerably less than the average, and the duration of the snowmelt runoff event was also about one month shorter than the average (Figure 3-5). The peak discharge in WY 2002 was only about 2,800 cfs, and the duration of the snowmelt runoff event was nearly 2.5 months shorter than normal (Figure 3-6). The peak discharge in WY2003 was about 20,000 cfs, but the duration of the snowmelt runoff was about one and a half months shorter than the average (Figure 3-7).

At the Cameo gage, it is evident that in the period between 1934 and 1949, the high-flow durations were greater, and the low-flow durations were less than in the 1950 to 2001 period (Figure 3-8). Water-resources development in the upper basin is the most likely explanation for the changes in the flow- duration curves. Based on the relatively short period of record for the Palisade gage, it is apparent that flows in the 15-MR are less than 1,100 cfs for more than 50 percent of the time, and only exceed 4,000 cfs about 16 percent of the time. Discharges of about 10,500 and 22,000 cfs, which represent half-bankfull (incipient motion) and bankfull (significant sediment transport) discharges, respectively, for the 15-MR (Pitlick et al. 1999), are equaled or exceeded about 7 percent of the time (about 26 days per year) and 2 percent of the time (8 days per year) on average.

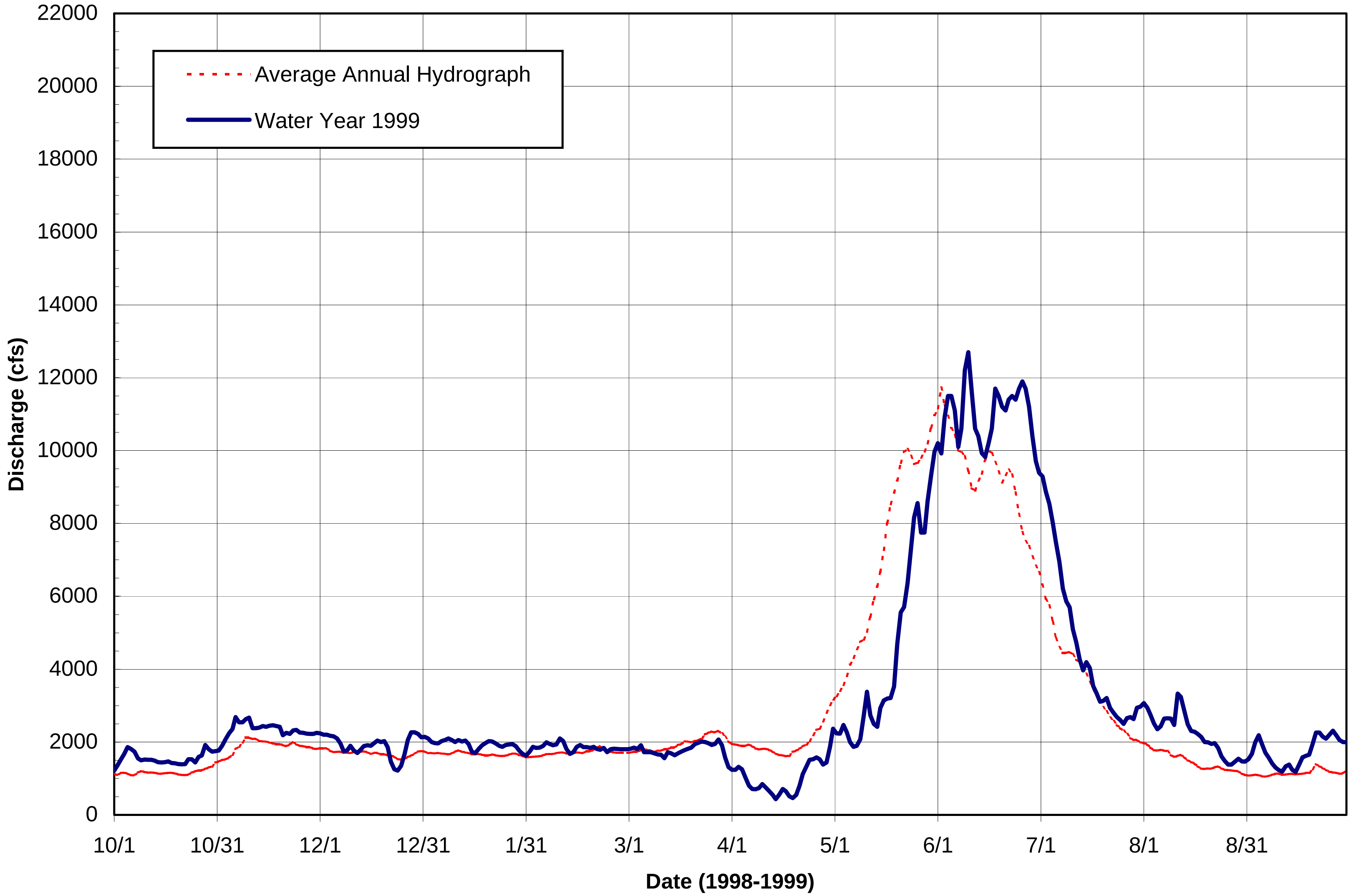


Figure 3-3. Annual hydrograph for the Palisade gage for WY 1999, with the average annual hydrograph superimposed.

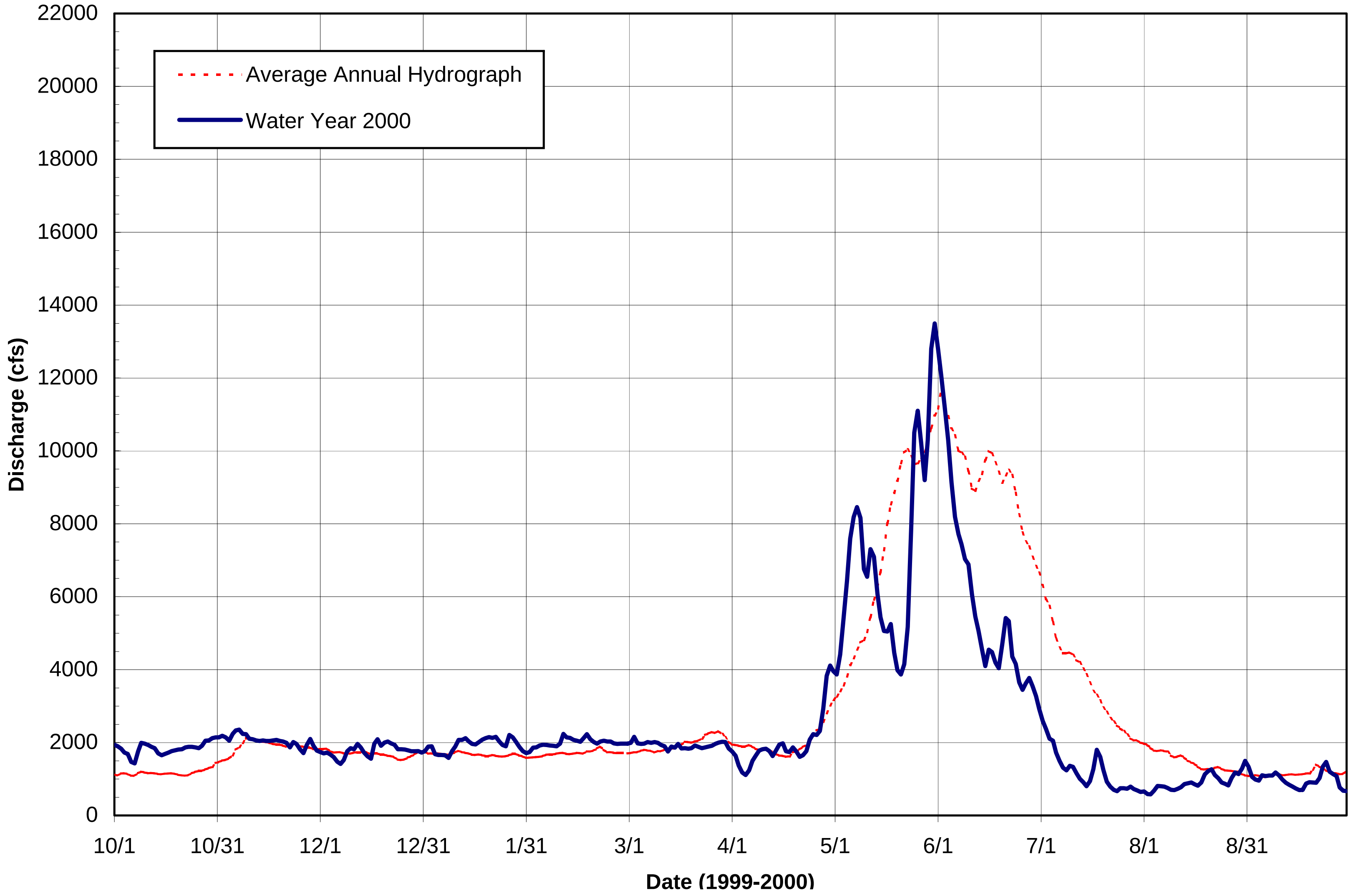


Figure 3-4. Annual hydrograph for the Palisade gage for WY 2000, with the average annual hydrograph superimposed.

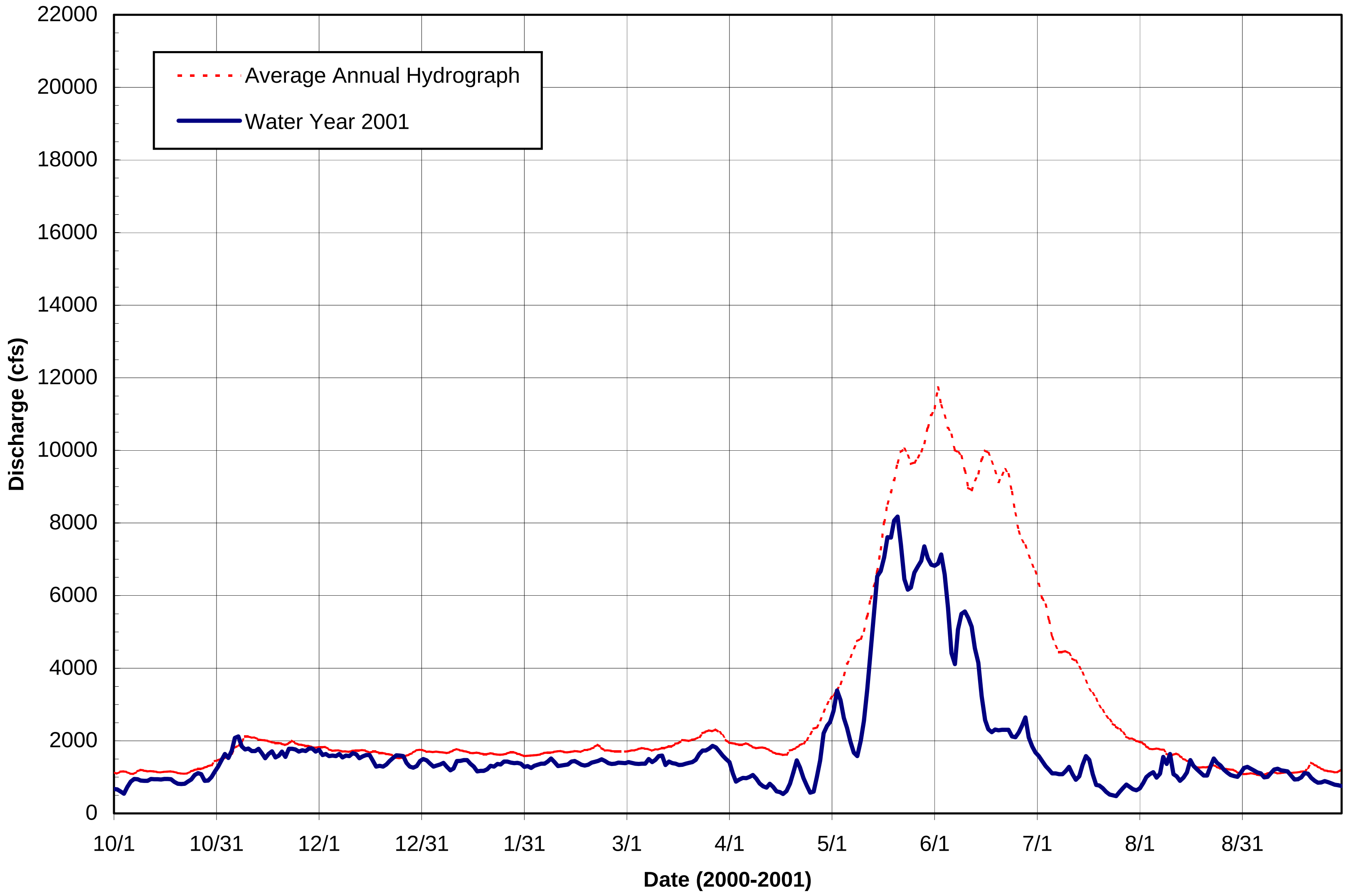


Figure 3-5. Annual hydrograph for the Palisade gage for WY 2001, with the average annual hydrograph superimposed.

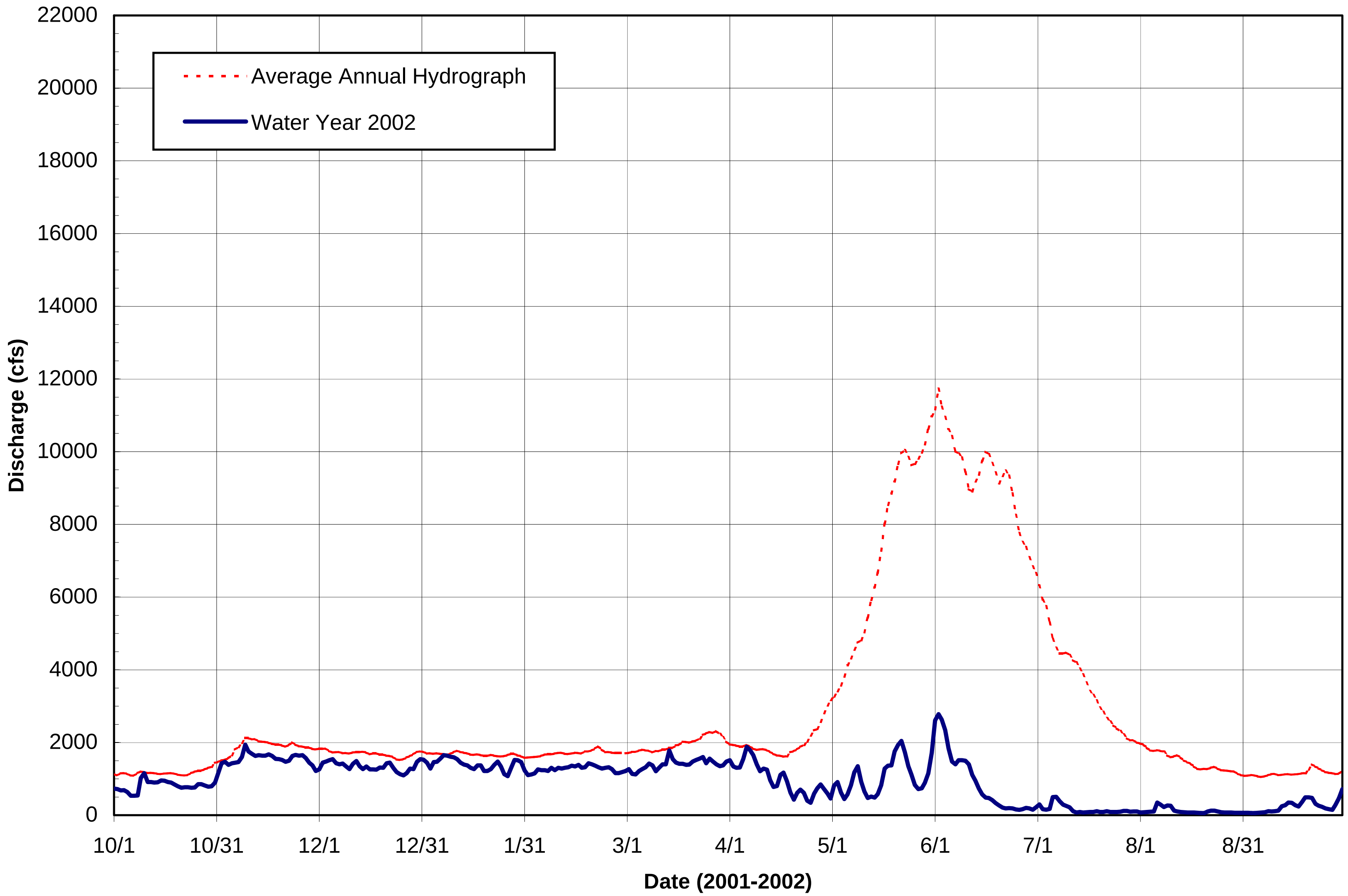


Figure 3-6. Annual hydrograph for the Palisade gage for WY 2003, with the average annual hydrograph superimposed.

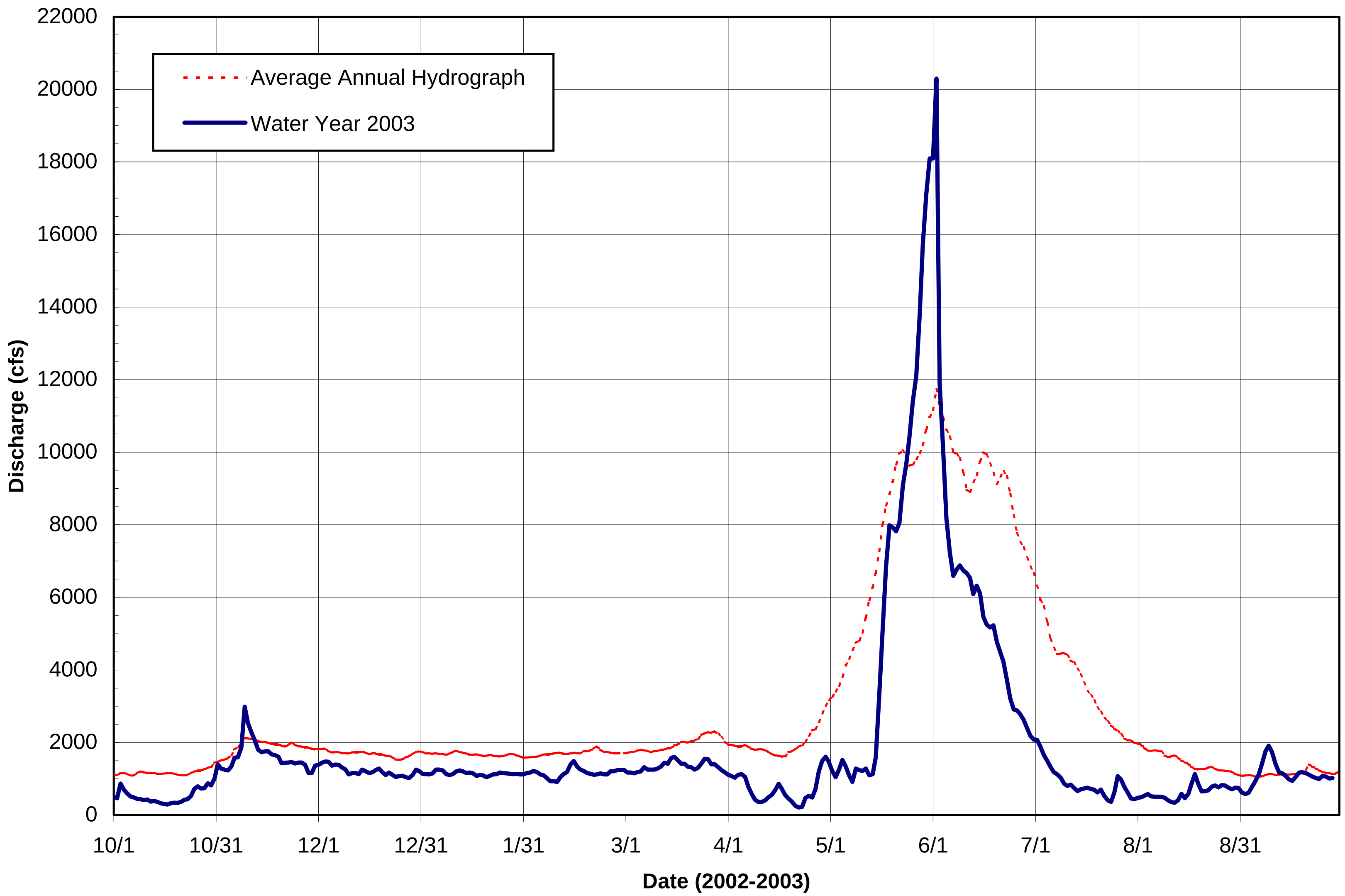


Figure 3-7. Annual hydrograph for the Palisade gage for WY2003 with the average annual hydrograph superimposed.

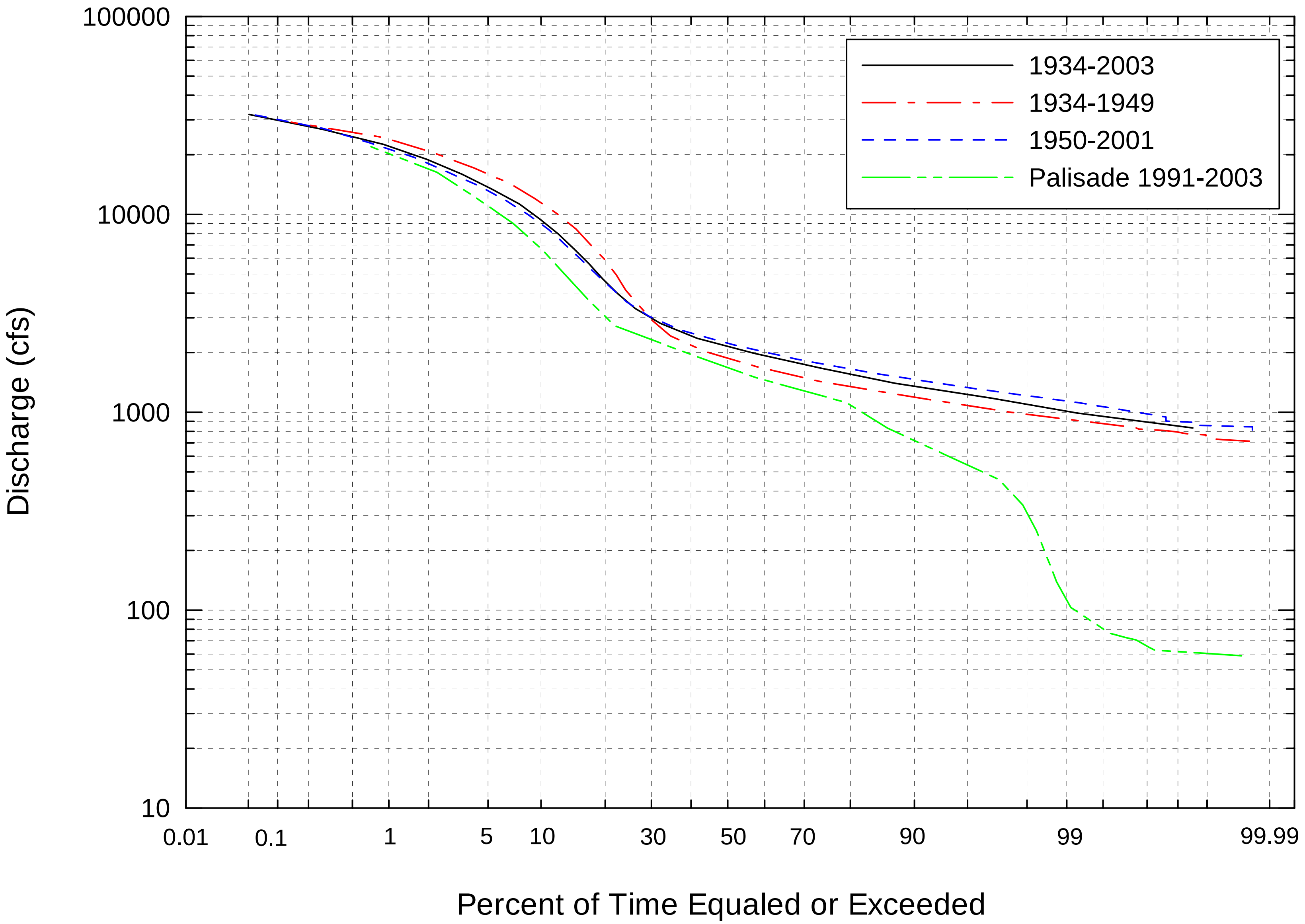


Figure 3-8. Flow-duration curves based on the mean daily flow record for the Cameo and Palisade gages.

3.1.2 Sedimentology

There is a distinct size difference between the surface armor sediments, subsurface sediments and fine surface sediments (Figure 3-9) at the Clifton site. The average median size (D_{50}) of the surface-armor sediments is 65 mm, and the D_{84} (the size of which 84 percent is finer) is 105 mm. The D_{50} of the subsurface sediments is 15 mm, and the D_{84} is 42 mm. In contrast to the surface sample where there are no sediments finer than gravels, about 33 percent of the subsurface sample is sand-sized and finer, and it is this finer fraction that represents the matrix sediments that support the coarser gravels. The D_{50} of the fine surface sediments (mud) is 0.07 mm, and the D_{84} is 0.16 mm. About 98 percent of this mud sample is sand- sized and finer (43 percent silts and clays). Because of the presence of the sand-and-gravel matrix in the subsurface sample, there is very little potential for deposition of the mud (very fine silts and clays) below the surface-armor layer. The absence of the mud from the subsurface sediments was confirmed visually by the freeze-core samples (Figure 3-10).

Along the right side of Cross Section 2 (run), where benthic macroinvertebrate and periphyton samples were collected, the lower bank samples are slightly coarser than the bed samples, with the D_{50} of the bank samples ranging from about 90 to 102 mm, and that of the bed of about 80 mm (Figure 3-11). Along the right bank at Cross Section 5 (riffle), where benthic macroinvertebrate and periphyton samples were collected, the D_{50} of the lower bank samples range from 65 to 85 mm, and those of the bed from 62 to 70 mm (Figure 3-12). The D_{50} of the surface sediments around the mid-channel bar ranges from 60 to 103 mm, and the D_{84} ranges from 111 to 146 mm (Figure 3-13). Gradation curves derived from sieve and hydrometer analyses for two samples of mud collected at the head of the mid-channel bar, that are representative of the sediments injected with silver nitrate and nickel chloride tracers, are shown on Figure 3-14. Mud sample gradation curves show that between 97 and 100 percent of the samples are sand-sized and finer, and the silt-clay content ranges from 42 to 64 percent.

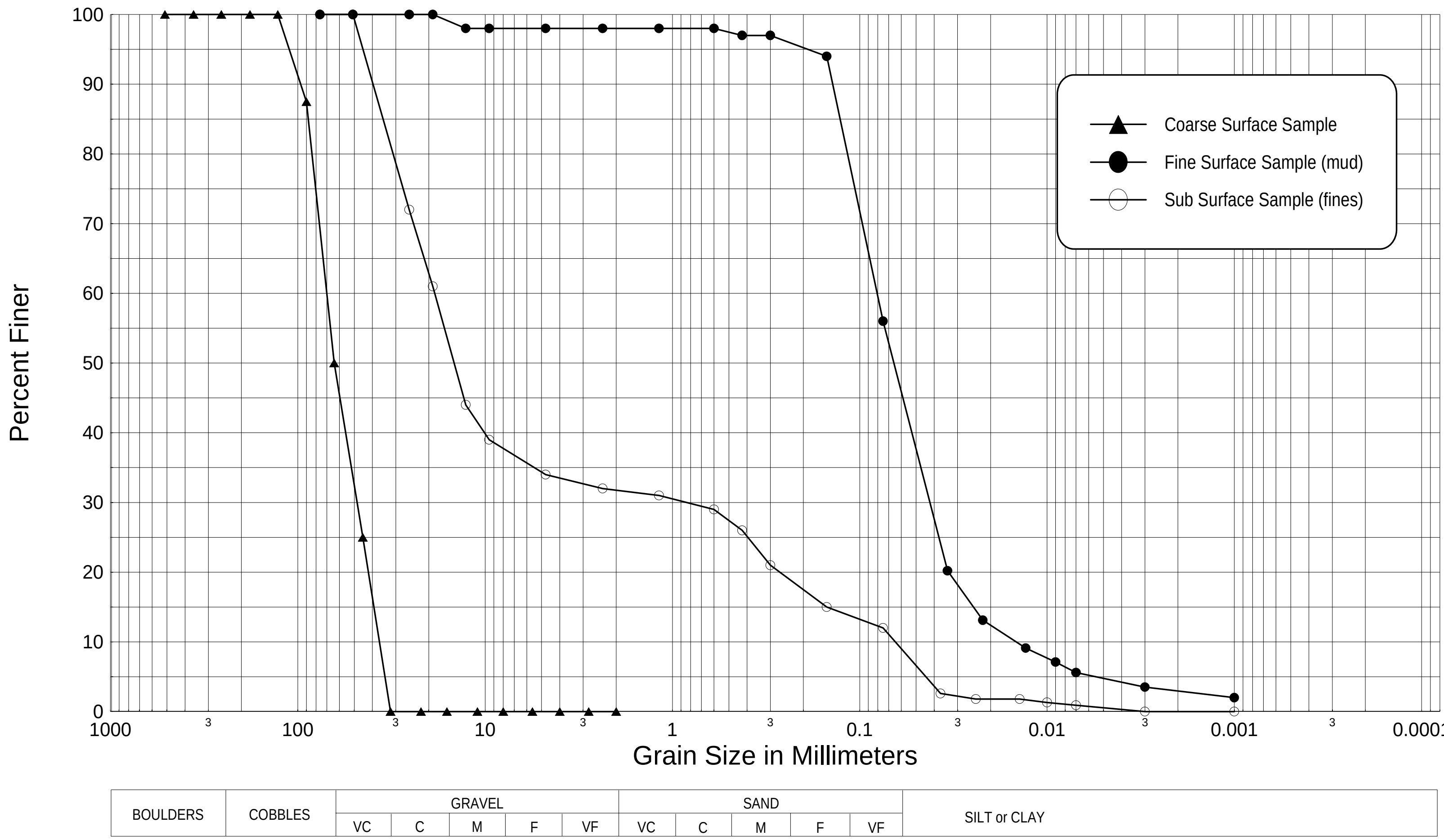


Figure 3-9. Grain-size distribution curves for Barrel Sample 3 (BS3) showing the gradations of the surface-armor layer, subsurface sediments and overlying muds. BS3 is located on the right side of the channel downstream of Cross Section 5 (Figure 3-5).

Figure 3-10. Photographs of freeze-core samples showing the mud layer on top of, and within, the surface armor layer, but not within the subsurface matrix sediments at Clifton.

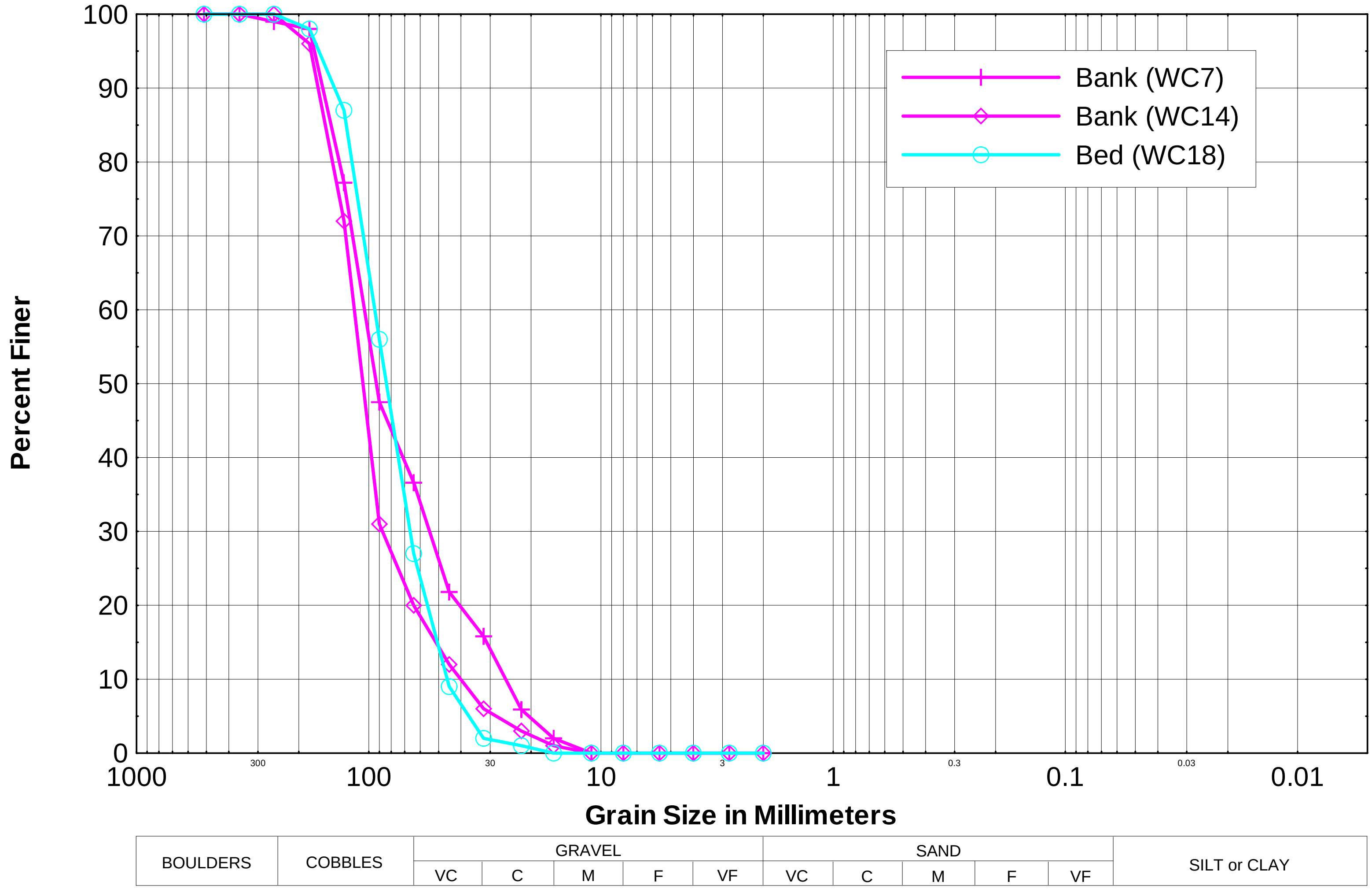


Figure 3-11. Grain-size distribution curves developed from Wolman pebble counts of the lower bank and bed samples at Cross Section 2. These samples represent the gradations of the coarse sediments that were involved in the biological sampling of the run habitat at various flows. (Refer to Figure 2-6 for locations of samples).

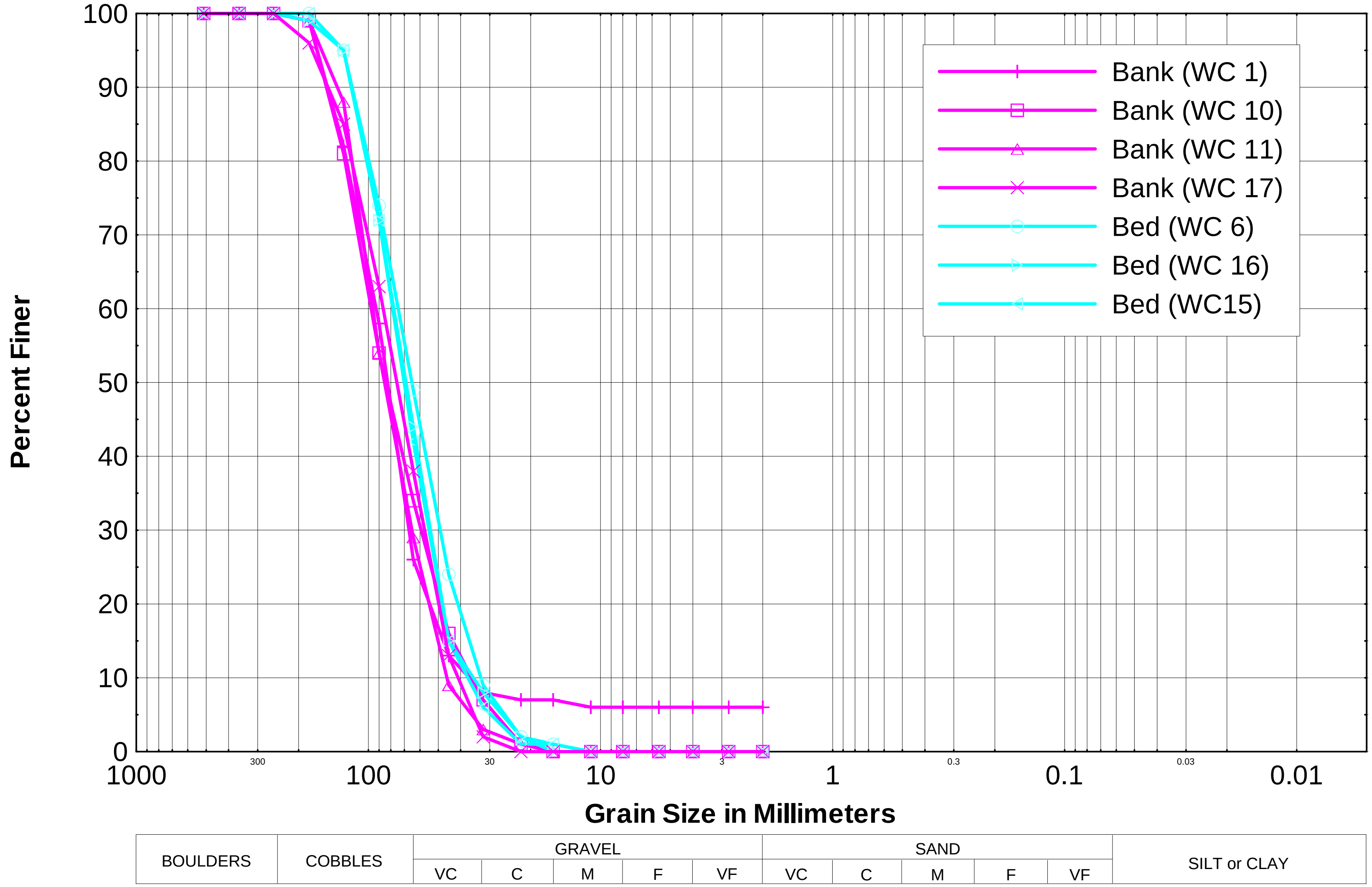


Figure 3-12. Grain-size distribution curves developed from Wolman pebble counts of the lower bank and bed samples at Cross Section 5. These samples represent the gradations of the coarse sediments that were involved in the biological sampling of the riffle habitat at various flows. (Refer to Figure 2-6 for the locations of the samples.)

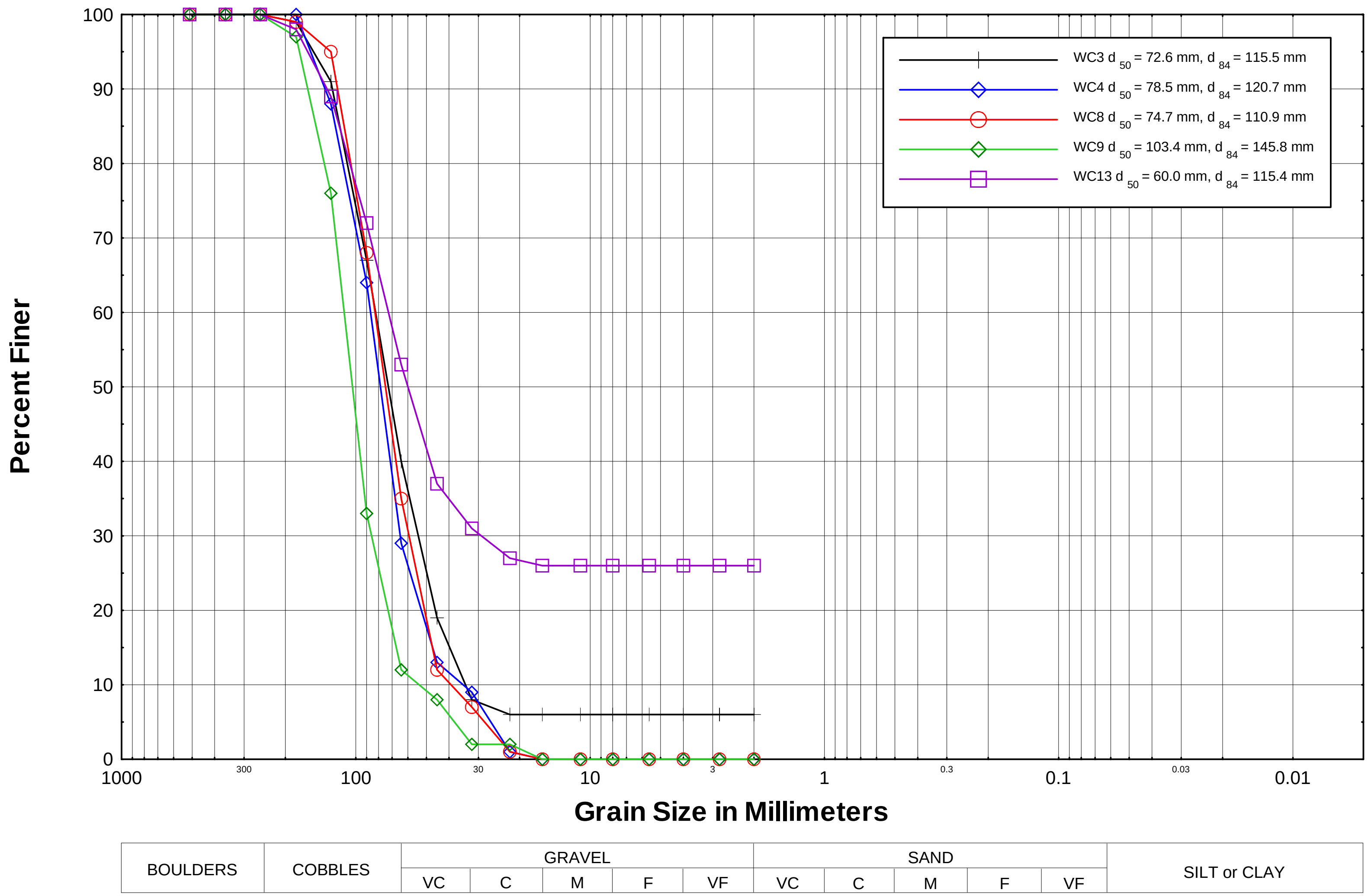


Figure 3-13. Grain-size distribution curves developed from Wolman pebble counts of the surface sediments that form the mid-channel bar at the Clifton site. (Refer to Figure 2-6 for locations of individual samples.)

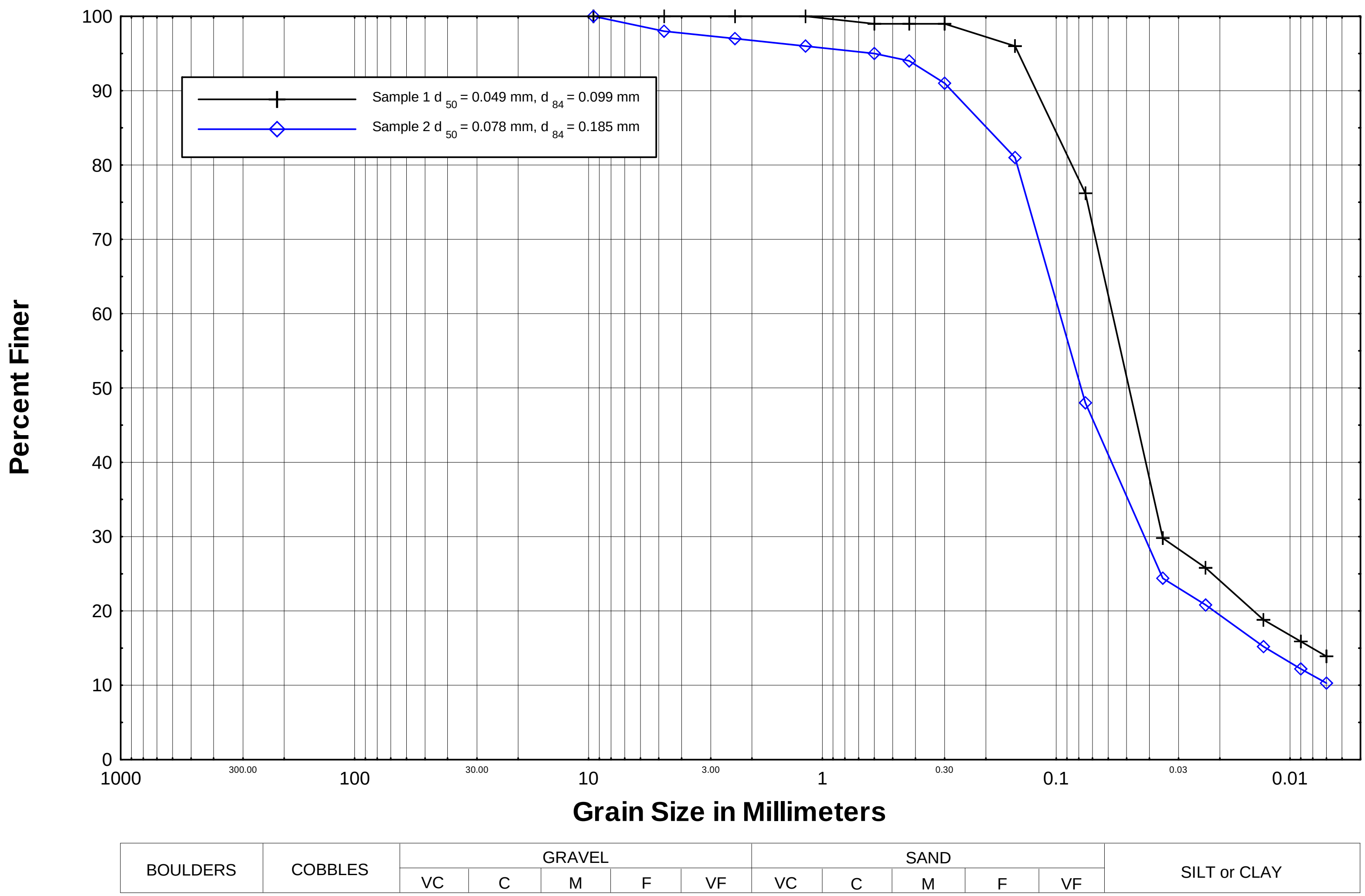


Figure 3-14. Grain-size distribution curves derived from sieve and hydrometer analyses for two mud samples that were collected from the head of the mid-channel bar, and are typical of the fine-grained sediments that were injected with Silver Nitrate and Nickel Chloride tracers.

The D_{50} of the riffle samples for the Corn Lake site (WC 1-5) ranges from 42 to 77 mm, and the D_{84} ranges from 90 to 111 mm (Figure 3-15). The run samples for this site (WC 6-8) have a D_{50} range of 48 to 57 mm and a D_{84} range of 84 to 94 mm. Freeze core samples (Figure 3-16) also show that the fine gravel and sand matrix within the subsurface sediments prevents ingress of the mud.

Comparison of the D_{50} values at the riffles and the runs at the two sites shows that the surface sediments at the Clifton site are somewhat coarser than those at the Corn Lake site, regardless of the location within the site. However, the differences in grain size do not appear to have a significant effect on the mud dynamics at the sites.

3.1.3 Turbidity and Suspended Sediment

In all years, the highest turbidity and estimated suspended sediment concentrations occurred in the post-runoff period (Figure 3-17). In 1999, highest turbidity values occurred during the tailend of the runoff season and extended into the post-runoff period. In 2000, the highest turbidities occurred about one month after the runoff. In 2001, the highest turbidities and suspended-sediment concentrations occurred during the post-runoff period when runoff from at least eight identified summer thunderstorms in the lower part of the basin introduced fine sediment to the river at relatively low discharges in the river (600 to 1,500 cfs, Figure 3-17). In contrast, during 2002, the high turbidity and estimated suspended-sediment concentrations occurred during both the runoff period and post-runoff thunderstorm period. This difference in the data between 2001 and 2002 can be explained by the relative magnitudes of the two runoff seasons. In 2001, the peak discharge during the runoff season was about 8,200 cfs at the Palisade gage, and the runoff season extended from early May to late June. In contrast, the 2002 runoff season had a peak discharge of about 2,800 cfs at the Palisade gage and extended from mid-May to mid-June. An early thunderstorm in the Plateau Creek basin in late March 2002 delivered a significant amount of mud to the 15-MR, as did flushing of the Roller Dam in late October 2001 (Figure 3-17). As a result, significant amounts of sediment were observed in the bed of the river prior to the onset of the runoff season, and it was this in-channel stored sediment that was mobilized during the low magnitude, short duration, runoff season and produced the

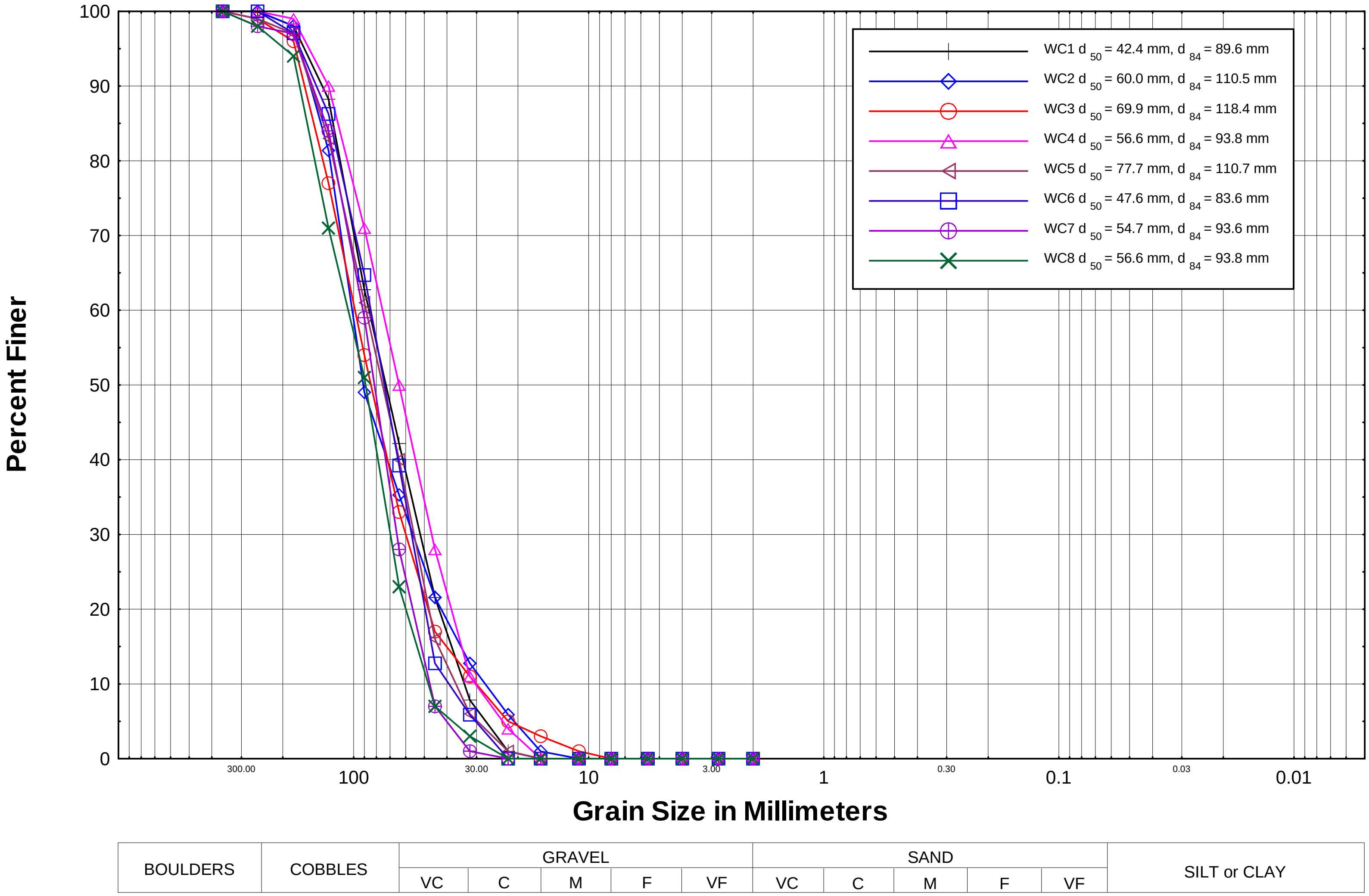


Figure 3-15. Grain-size distribution curves developed from Wolman pebble counts of the sediments that form the riffle and run at the Corn Lake site. (Refer to Figure 2-3 for the locations of the individual samples.)

Figure 3-16. Photographs of freeze-core samples showing the mud layer on top of, and within, the surface armor layer, but not within the subsurface matrix sediments at Corn Lake.

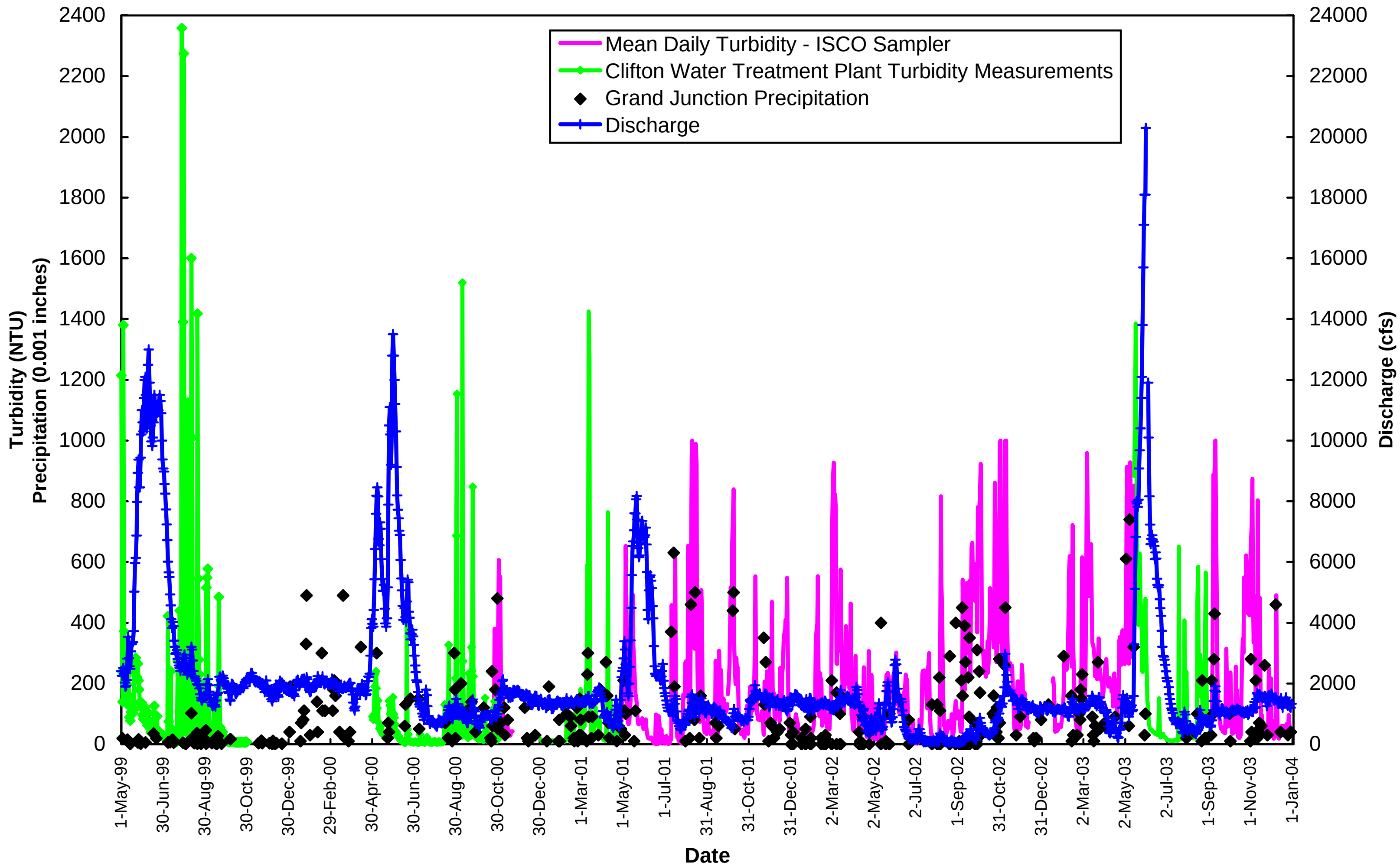


Figure 3-17. Summary of mean daily turbidity values at Clifton site, mean daily discharge at Palisade gage, and precipitation at Grand Junction airport from October 2000 to January 1, 2004.

high suspended-sediment concentrations, some of which were on the same order as the summer thunderstorm-generated values.

Turbidity values recorded during the 2002 post-runoff season (Figure 3-17) indicate that there were few periods of elevated turbidity in the early part of the post-runoff period, which correlates with the general absence of rainfall-producing thunderstorms during the current drought period. Elevated turbidities occurred in the Fall when the frequency of rain events increased. Additionally, because of drought conditions, the flows in the 15-MR during the post-runoff period in 2002 were extraordinarily low (70 to 500 cfs). In 2003, following a high peak discharge (20,000 cfs), higher turbidity events occurred throughout the post-runoff period. The elevated turbidities in late October-early November were due to flushing of an upstream dam.

Davies-Colley and Smith (2001) provided a thorough review of the relationships between turbidity, suspended sediment, and water clarity. They noted that suspended sediment could have a number of environmental impacts on water bodies that included transport of adsorbed pollutants, benthic smothering, and optical impacts that included reduced photosynthesis and reduced visual range of sighted organisms. Davies-Colley and Smith (2001) and Henley et al. (2000), further cautioned that the use of turbidity measurements (NTU) without cross-calibration to an absolute quantity such as suspended-sediment concentration or water clarity (Secchi disc measurements) is of little environmental value. No universal relationship of suspended-sediment concentration to turbidity or water clarity exists, and therefore, site-specific relationships must be developed empirically. Silt- and clay-sized particles (<0.062 mm) have been shown to dominate light attenuation in natural water bodies (Davies-Colley et al. 1993; Kirk 1988). Correlations between suspended-sediment concentrations and turbidity (Lloyd et al. 1987) as well as turbidity and water clarity (Davies-Colley and Close 1990) have been developed for specific rivers.

Development of a site-specific relationship between suspended-sediment concentration and turbidity for the Clifton site was hampered by two factors. First, when the sampler was initially installed the software that controls the time stamps on the data offset the time stamp for the suspended-sediment samples, and therefore, the values for suspended-sediment concentration and turbidity were not synchronous. The sampler manufacturer has since developed a software patch. Unfortunately, no specific correction factor could be applied to the older data. Second, the turbidity meter has an upper limit of 1,000 NTU. Review of daily turbidity data supplied by the Clifton Water Treatment Plant indicated that NTU values in excess of 10,000 were recorded by their laboratory instrumentation. The net effect is that the turbidity values were capped at 1,000 NTU, and did not, therefore, record the higher values that would have been correlated with the highest suspended-sediment concentrations. The effects of the capping of the turbidity values are apparent, and are reflected in the poor correlation for the Clifton site ($R^2 = 0.4$) (Figure 3-18):

$$Y = 0.2062X^{1.09} \tag{10}$$

Secchi disc measurements were made in the project reach by the benthic sampling crew. The relationship between the turbidity (Y:NTU) at the sampler and the Secchi disc extinction depth (X:ft) shows a strong inverse relationship ($R^2 = 0.97$), and it quantifies the relationship between turbidity and water clarity at the site (Figure 3-19):

$$Y = 58.42X^{-1.28} \tag{11}$$

The relationship between turbidity and discharge at the Clifton site is temporally varied (Figure 3-17). Additional data supplied by the Clifton Water Treatment Plant show similar temporal trends as the mean daily data. Turbidity values tend to rise rapidly with the onset of the runoff season, and then decline very rapidly during the remainder of the runoff season until runoff from summer thunderstorms in the basin provides a new source of fine sediment. The rapid increase in turbidity values and the rapid decline within a short time from the onset of the runoff suggests that the source of the fine sediments that are the primary cause of the increased turbidity (Davies-Colley et al. 1993; Kirk 1988), are the sediments that were deposited within the channel and on the channel margins by slightly elevated summer thunderstorm-generated flows or during recessional flows of the previous snowmelt runoff season.

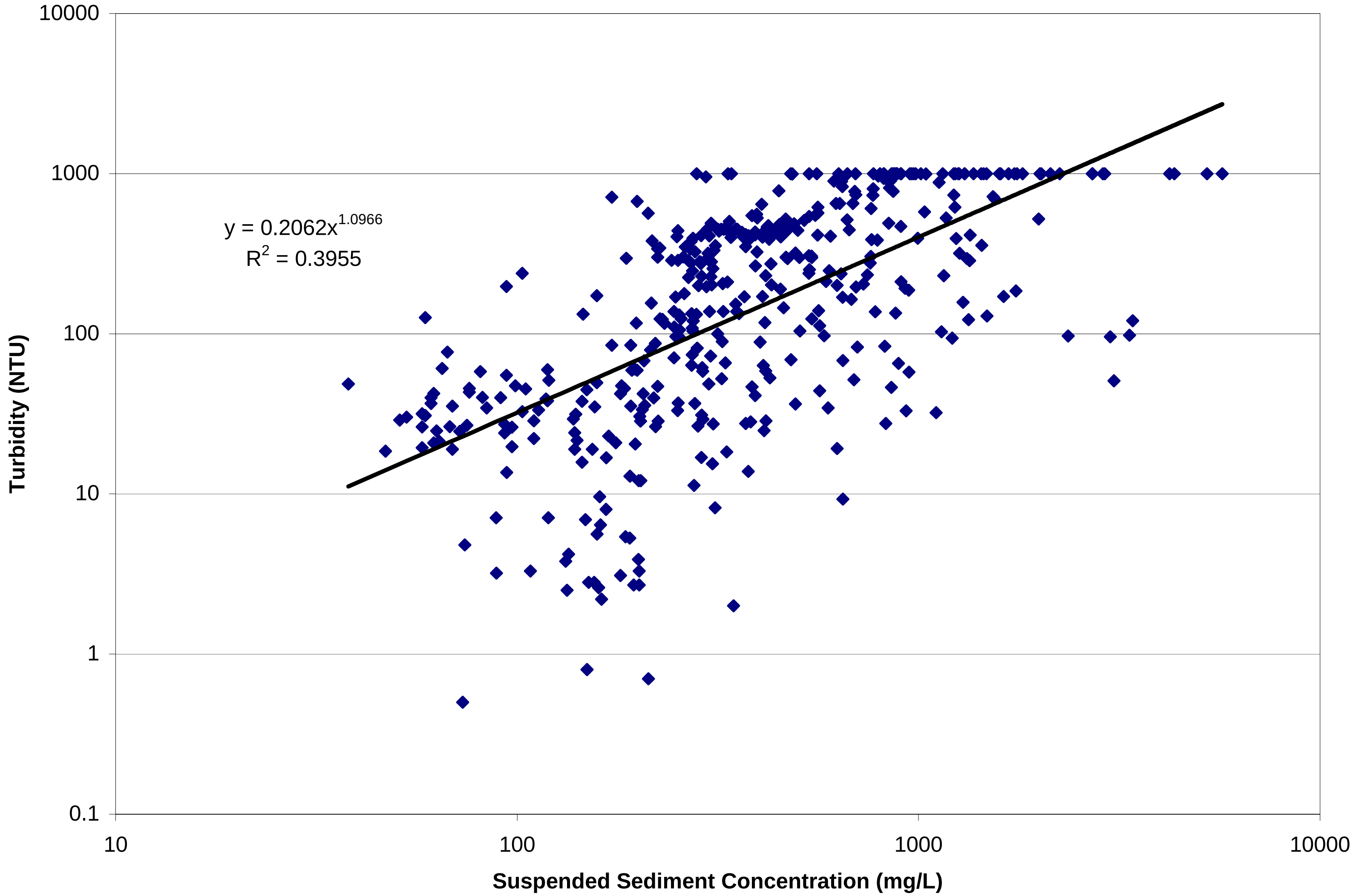


Figure 3-18. The relationship between suspended-sediment concentration and turbidity at the Clifton site.

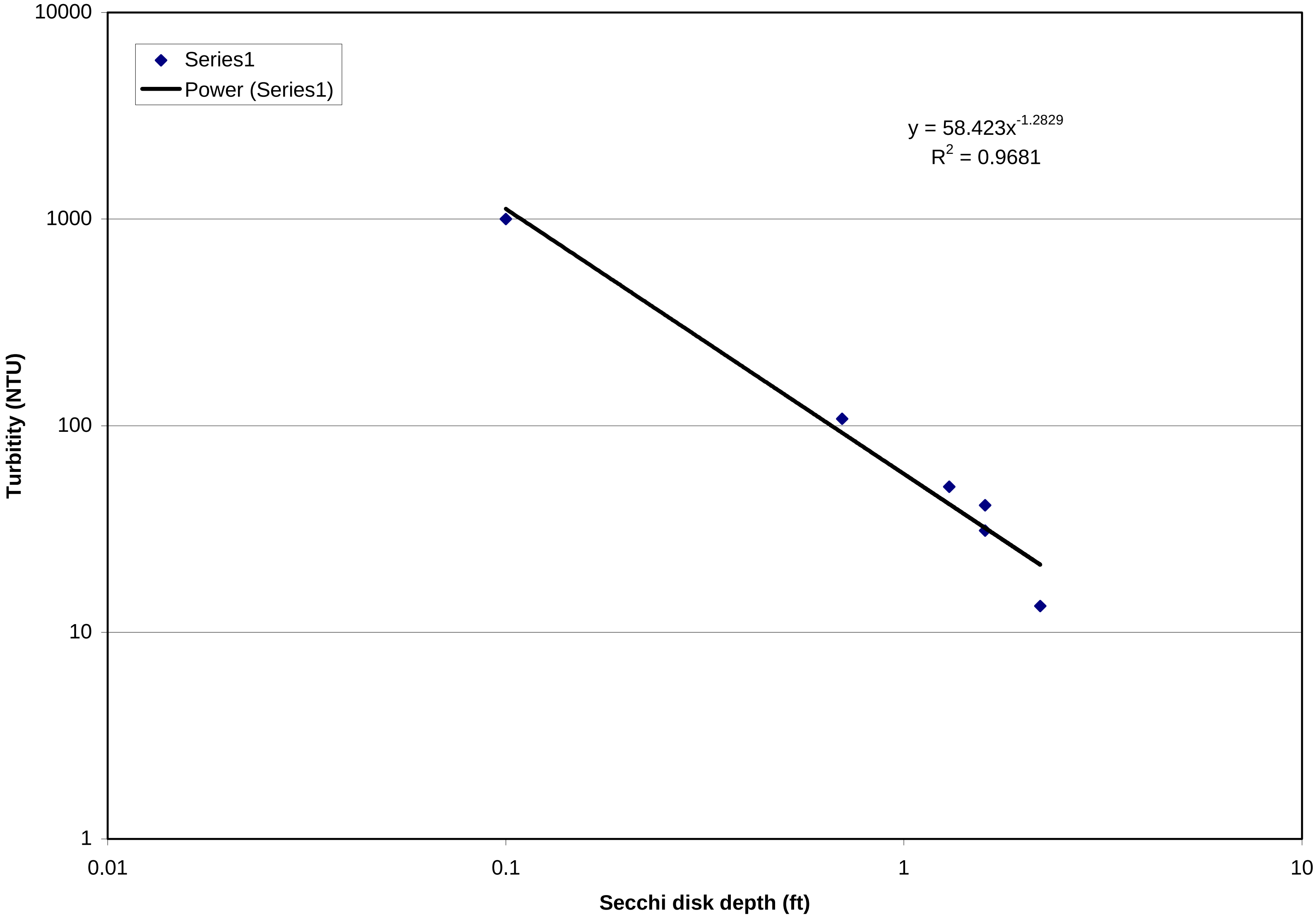


Figure 3-19. The relationship between Secchi disc extinction depth and turbidity at the Clifton site.

Locations within the channel where velocities are low during the post-runoff period are inundated by the increasing flows during runoff and it appears that the previously deposited fine sediments are re-entrained. Based on the turbidity data for WY 2000, WY 2001, and WY 2002 (Figure 3-17), it appears that most of the in-channel supply of fine sediment may be exhausted by the time the discharge is on the order of about 3,000 cfs on the rising limb of the snowmelt hydrograph. The turbidity data also show that there were few summer thunderstorm runoff events in WY 2000, a significant number in WY 2001, a few in WY 2002 and a significant number in WY2003. The presence or absence of turbidity events in WY 2000, WY2001, WY 2002 and WY2003 correlate well with precipitation records for the Grand Junction airport and Rifle measurement stations during the post-runoff period (Figure 3-17).

It is important to be able to relate the turbidity values to the suspended-sediment concentrations because of the biological implications. Turbidity values (>400 NTU) were used to trigger the suspended-sediment sampling in the post-runoff period. Comparison of the data sets indicates that the turbidity-identified events do in fact correlate with the elevated suspended-sediment concentrations, even though the absolute relationship between turbidity and suspended-sediment concentration is not strong (See appendix). Therefore, it is reasonable to use the turbidity measurements as a non-quantitative indicator of elevated suspended-sediment concentration events that result in mud deposition and the related biological effects at the Clifton site.

From early April 2001 to the end of December 2003, records were maintained of water temperature, conductivity, and specific conductance for the Clifton site. Water temperatures are depressed during the winter (about 2°C), climb upwards during the snowmelt runoff season to about 15.5°C, and are at their highest during the summer low-flow period where they fluctuate in a normal year between 21°C and 27°C. With the very low discharges in the post-runoff period in WY 2002, water temperatures have exceeded 30°C (Figure 3-20).

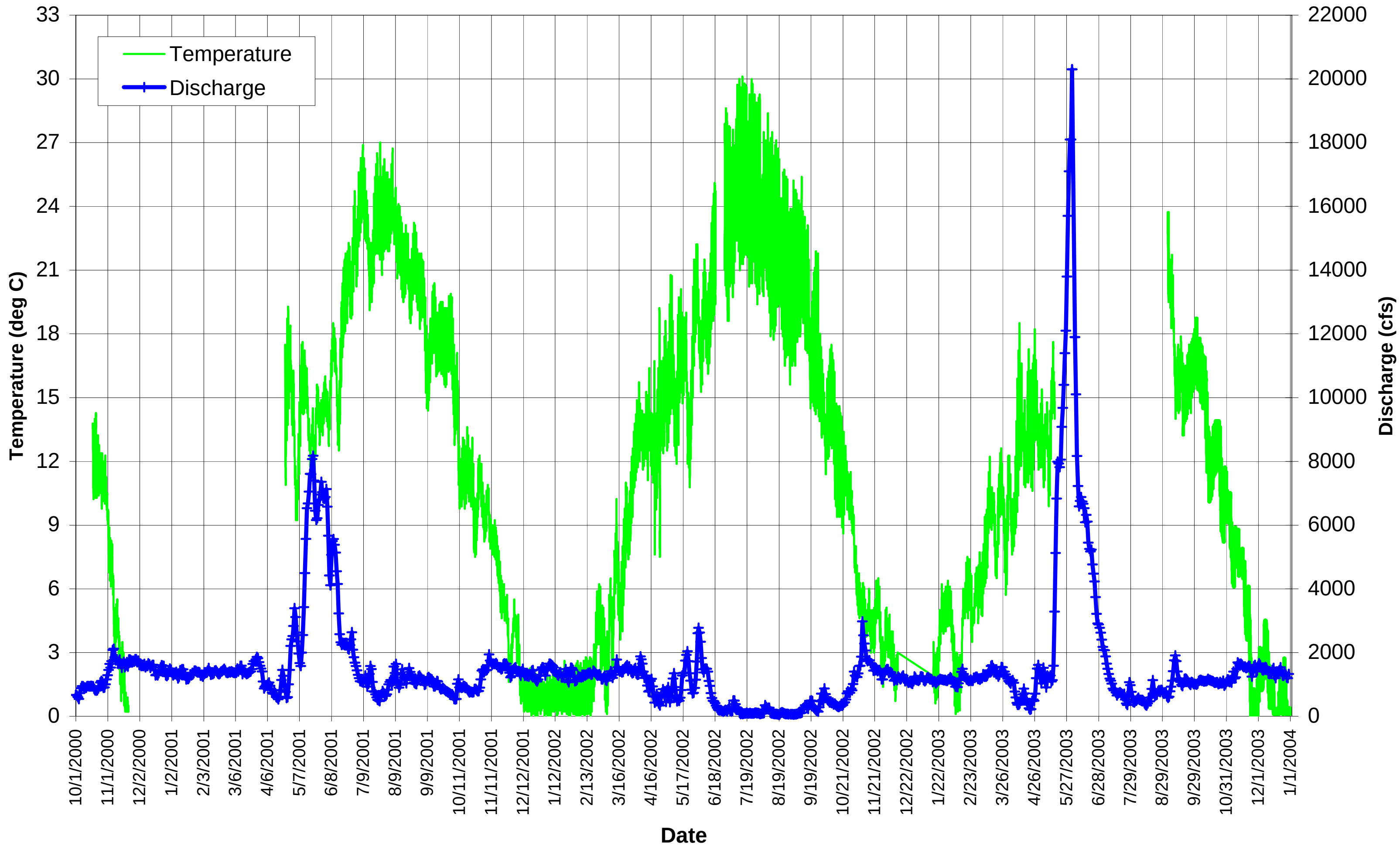


Figure 3-20. Summary of discharge and water temperature data for the Clifton site, WY 2001 to January 1, 2004.

Water-conductivity measurements show an inverse relationship to discharge, with low values at higher discharges during the snowmelt runoff season, and higher values during the low-flow periods of the year (Figure 3-21). Specific conductance (conductivity adjusted to a temperature of 25^{o}C) values show the same trends as the water-conductivity data which is an inverse relationship to discharge, with low values at higher discharges during the snowmelt runoff season, and higher values during the low-flow periods of the year (Figure 3-22) and both correlate well with the USGS data from the Cameo gage.

3.1.4 Spatial Distribution of Mud Deposits at Clifton and Corn Lake Sites

Mud deposition at the Clifton site is clearly related to the channel margins (Figure 3-23). The greatest amounts of mud are associated with the margins of the channel and bars where the flow depths and velocities are the lowest. It is reasonable, therefore, to assume that the boundaries for the individual mud class mapping units will shift with increases or decreases in discharge, and that the measured depth and velocity data can be used to define thresholds for the various mud classes that will apply to all discharges. The defined thresholds then can be used to predict the spatial distribution of the mud classes for discharges that are retained within the channel, provided that the depth and velocity distributions throughout the site are known, or can be estimated by modeling. In the portion of the site which was unmapped, because of the flow depths and velocities, it is reasonable to assume that there was no mud present, especially in the upper two-thirds of the site where the left bank is composed of Mancos Shale outcrop. Since there was good correlation between the field measurements of depth and mean column velocity and the output from the 2-D model, the mud distribution for the unmapped portion of the site was estimated from the 2-D output (Figure 3-23).

The velocity data show that velocity thresholds are apparent between the various mapped mud classes (Table 3-1, Figure 3-24). Because the individual mud classes overlap, the mid-points between the mean values were used to define the velocity thresholds between the various classes (Table 3-1). T-tests of the mean velocities ($P<0.1$) for the individual mud classes show that the mean values are significantly different among all of the mud classes, and the velocity values within each class are also normally distributed.

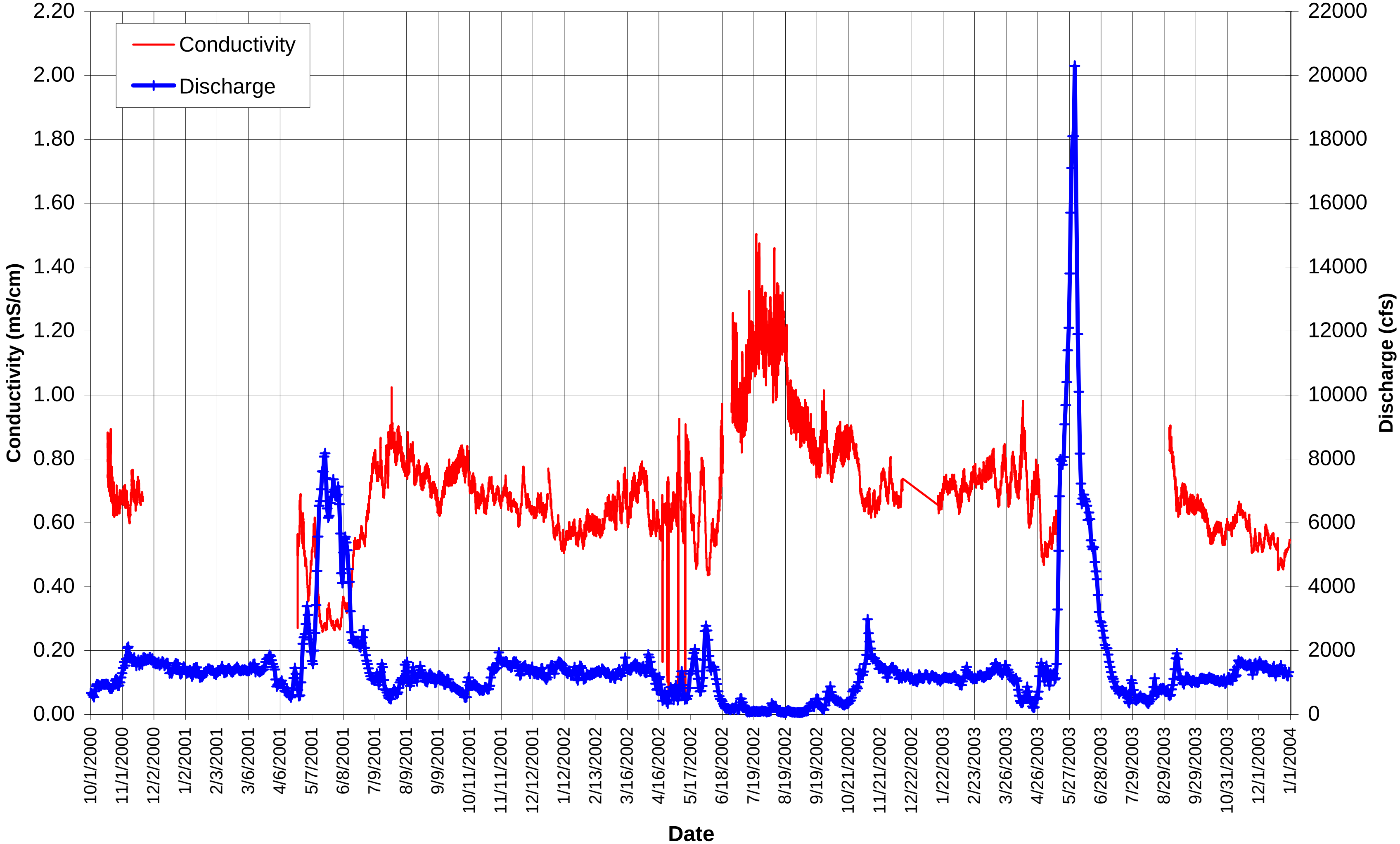


Figure 3-21. Summary of conductivity and discharge data for the Clifton site, WY 2001 to January 1, 2004.

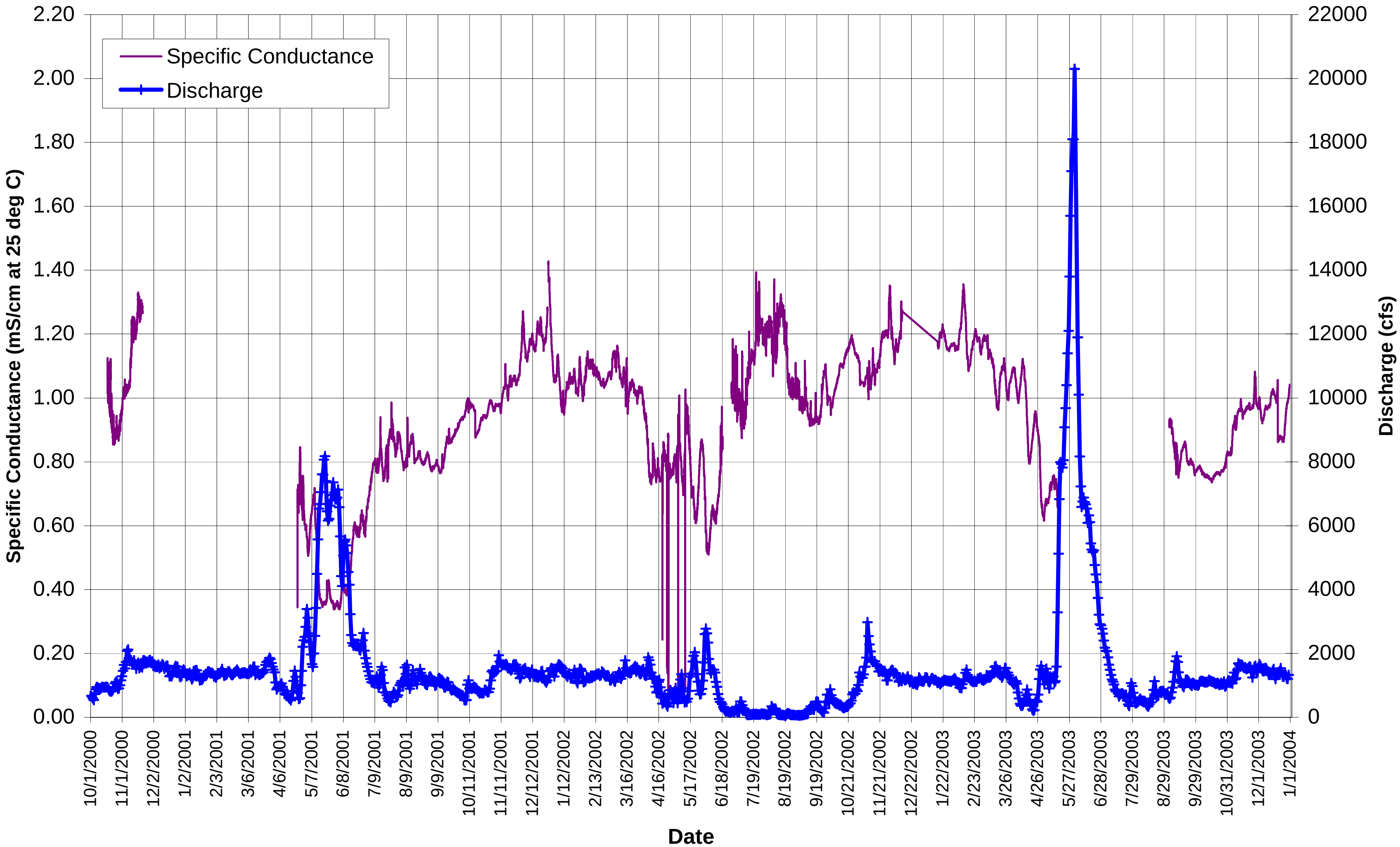


Figure 3-22. Summary of specific conductance and discharge data for the Clifton site, WY 2001 to January 1, 2004.

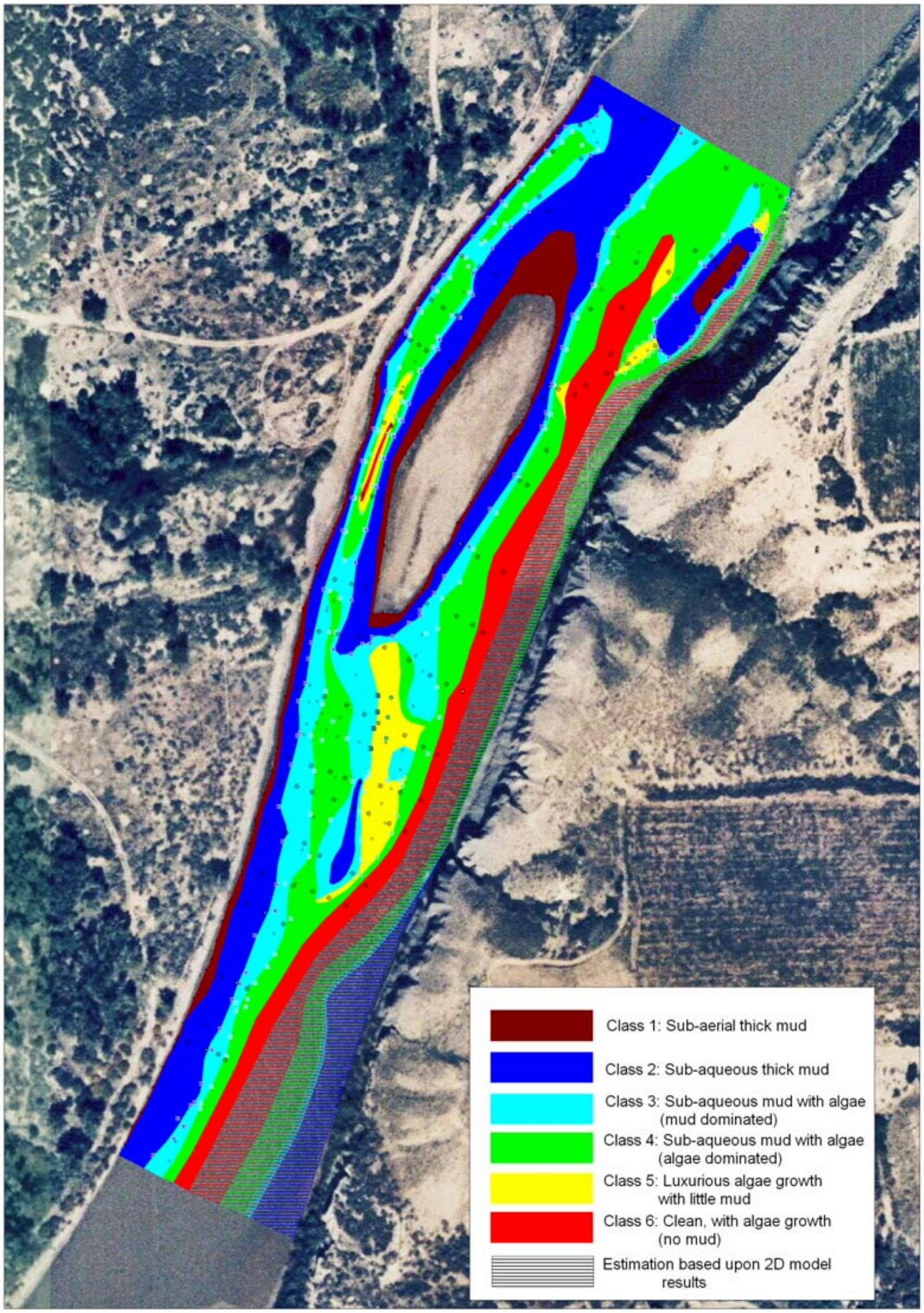


Figure 3-23. Map showing the distribution of mud deposits at the Clifton site on August 28 and 29, 2001, when the discharge was 1,030 cfs. The locations of the depth and velocity measurements within the boundaries of the various mapping units are also shown as dots. Hatched areas are estimated from 2-D model output of depths and velocities at a discharge of 1,100 cfs.

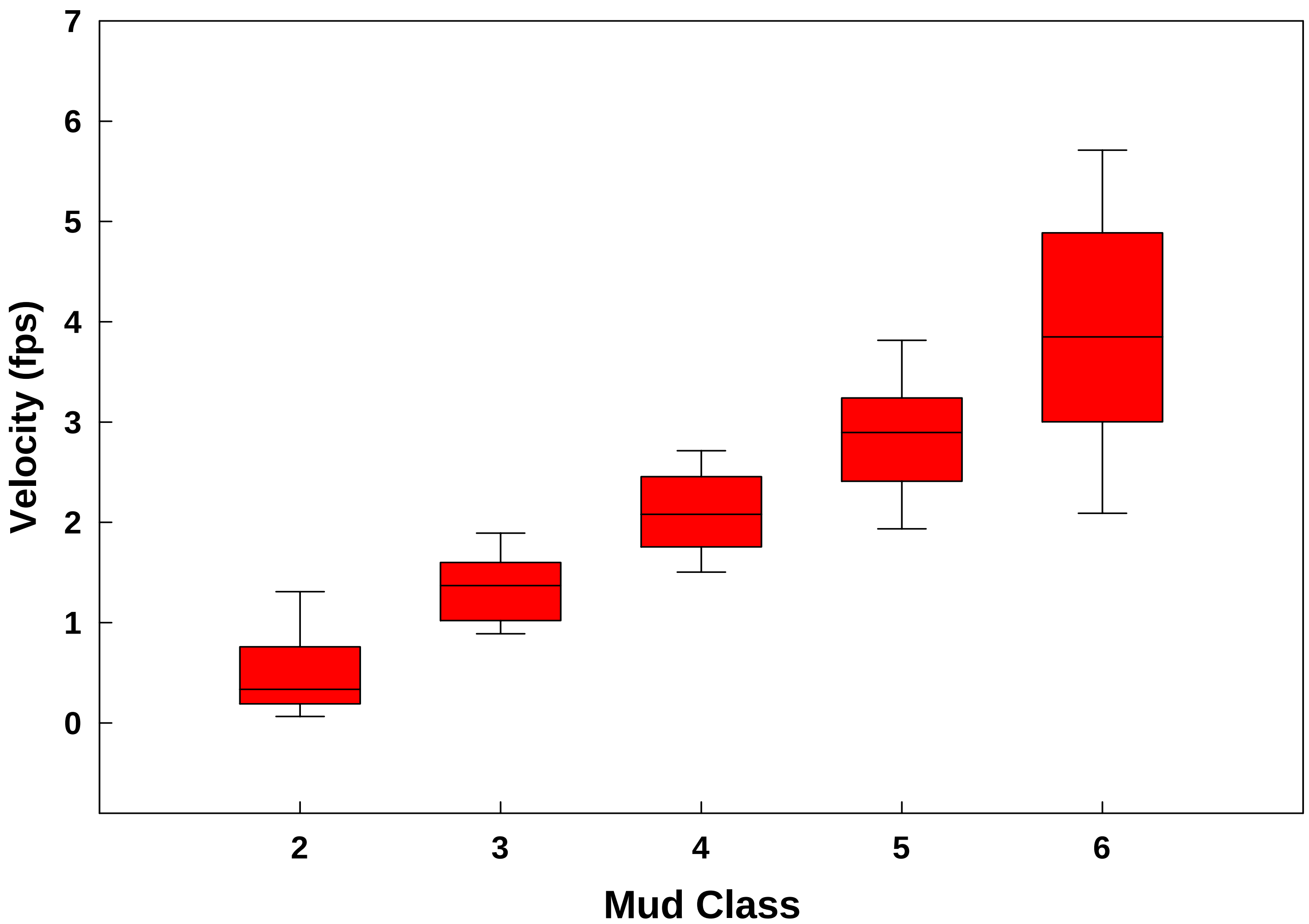


Figure 3-24. Box-and-whisker plots of the velocities for the individual subaqueous mud classes based on the measurements at Clifton. For the individual classes, the top of the whisker represents the 90th percentile, the top of the box represents the 75th percentile, the center of the box represents the median value, the bottom of the box represents the 25th percentile, and the lower whisker represents the 10th percentile.

Table 3-1. Descriptive statistics for measured velocities (fps) for the individual subaqueous mud classes at Clifton.

Parameter	Class 2	Class 3	Class 4	Class 5	Class 6
Number of Values	30	34	29	10	15
Minimum	0	0.4	1.2	1.7	2
Median	0.3	1.4	2.1	2.9	3.9
Maximum	1.4	2.4	2.9	3.9	5.6
Mean	0.5	1.4	2.1	2.9	3.9
Standard Deviation	0.08	0.08	0.08	0.21	0.32
Range	1.4	1.9	1.7	2.3	3.8
Threshold Values	<0.95	0.95-1.8	1.8-2.5	2.5-3.4	>3.4

When suspended-sediment concentrations are high, substantial mud deposition takes place at mean column velocities up to about 1.8 fps (classes 2 and 3). Mud deposition occurs but algal growth is visible up to a mean column velocity of about 2.5 fps (class 4). At mean column velocities above 2.5 fps (classes 5 and 6), there do not appear to be any observed mud effects on the algae. Casual observations of the individual gravel- and cobble-sized clasts that were removed from the channel bed at the time of the depth and velocity measurements, suggests a correlation between the mud effects and the presence of macroinvertebrates. At locations with substantial mud present (classes 2 and 3), there were few if any macroinvertebrates observed. Some macroinvertebrates were observed at class 4 sites, and numerous macroinvertebrates were observed at classes 5 and 6 sites.

To determine whether shear stress would provide a better threshold between the mud classes shear stress was calculated using the Darcy-Weisbach formula for each location where measurements of depth and velocity were made:

$$\tau = \frac{f\rho V^2}{8} \tag{12}$$

where τ is shear stress (lb/ft^2), ρ is the specific weight of water (lb/ft^3), v is the velocity (fps) and f is the friction factor 0.02 (Simons and Sentürk 1976). The procedure used to estimate shear stress for purposes of evaluating mobilization of the muds differs from that used to evaluate incipient motion of the gravels and cobbles. Rather than estimating the grain shear stress, which is based on the sizes of the individual particles that make up the bed of the river, a friction factor for fine sediment was used because when mud is present on the bed, the bed is smoothed.

The data for Clifton show that shear-stress thresholds are present between the various mapped mud classes (Figure 3-25, Table 3-2). Because the individual mud classes overlap, the mid-points between the mean values were used to define the thresholds between the various classes (Table 3-2). T-tests of the mean shear stresses ($P<0.1$) for the individual mud classes show that the mean values are significantly different between all of the mud classes, and the shear stress values within each class are also normally distributed. Substantial mud deposition takes place at shear stresses up to about 0.02 lb/ft^2. Visible mud is present up to a shear stress of about 0.03 lb/ft^2. At shear stresses above 0.03 lb/ft^2, there does not appear to be any mud deposition.

Table 3-2. Descriptive statistics for computed shear stress (lb/ft^2) for the individual subaqueous mud classes at Clifton.

Parameter	Class 2	Class 3	Class 4	Class 5	Class 6
No. Values	30	34	29	10	15
Minimum	0	0.001	0.007	0.014	0.019
Median	0.001	0.009	0.021	0.041	0.072
Maximum	0.009	0.027	0.041	0.075	0.16
Mean	0.002	0.01	0.022	0.042	0.08
Standard Deviation	0.001	0.001	0.002	0.006	0.012
Range	0.009	0.026	0.034	0.061	0.142
Threshold Values	<0.006	0.006-0.02	0.02-0.03	0.03-0.06	>0.06

The threshold values derived from the Clifton shear stress data are very consistent with values for deposition and entrainment that have been published from other studies of cohesive and fine-grained sediments. Partheniades (1965) and Partheniades and Kennedy (1973) demonstrated that erosion of fine-grained and cohesive sediments is independent of the shear strength of the bed material and of the concentration of suspended sediment, but that erosion depends strongly on the available shear stress. Erosion of fines increases rapidly after a critical value of the shear stress has been reached. Chow (1959) reported ranges in critical sheer stress values from 0.02 lb/ft^2 to 0.06 lb/ft^2 depending on the sand content. Graf (1971) indicated critical values of 0.015 lb/ft^2 for low plasticity clays and 0.1 lb/ft^2 for high plasticity clays. Smerdon and Beasley (1961) showed that a shear stress value of 0.03 lb/ft^2 differentiated

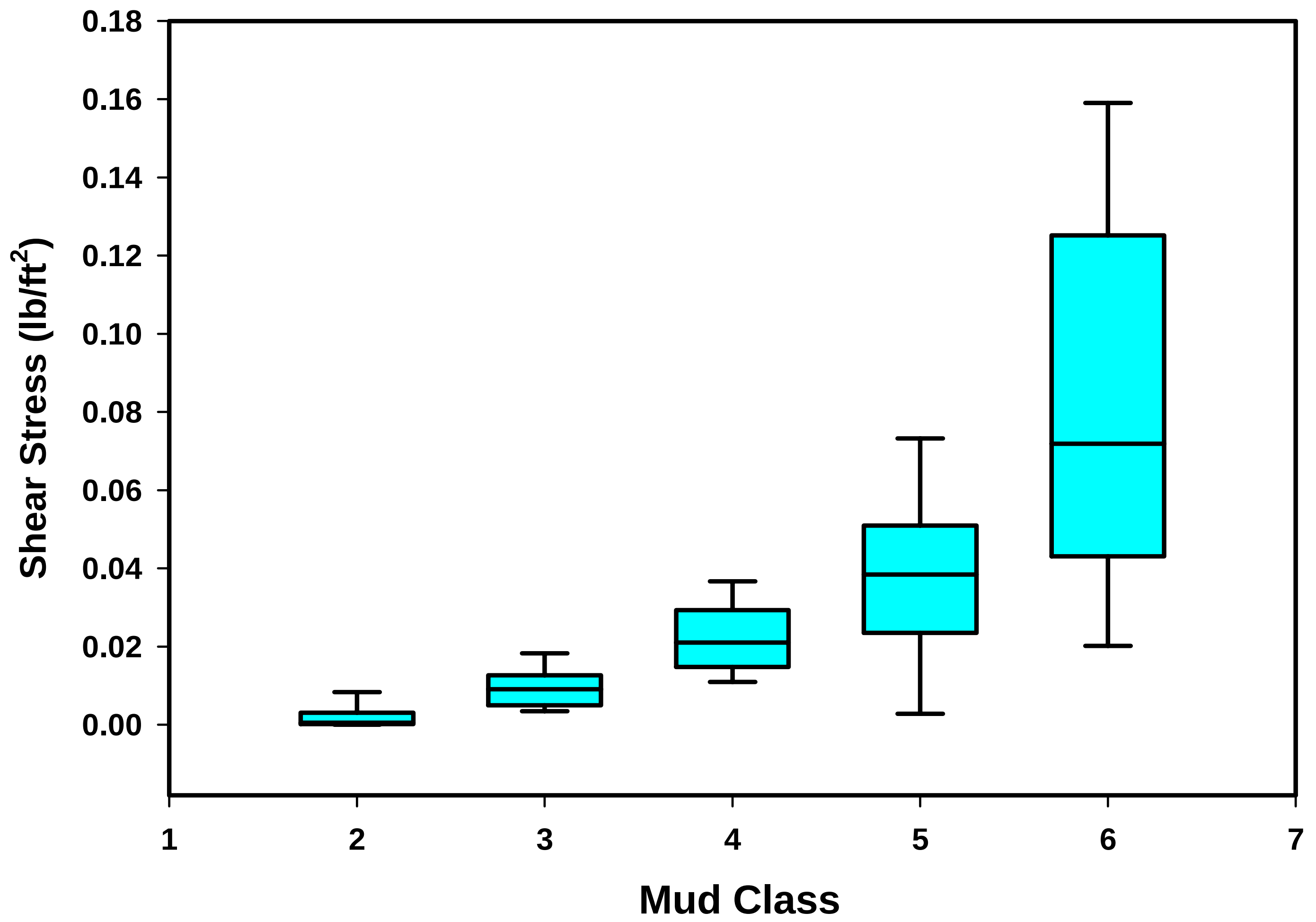


Figure 3-25. Box-and-whisker plots of shear stresses for the individual subaqueous mud classes based on the measurements at Clifton.

between deposition and erosion of low plasticity index (<20) soils, which are very similar to values for the muds deposited on the bed of the river at Clifton. Haralampides et al. (2003) showed experimentally that a shear stress of about 0.02 lb/ft^2 identified a threshold for deposition of fine grained sediments (D<0.075 mm).

The Corn Lake shear stress data show that velocity thresholds are present between the various mapped mud classes (Table 3-3, Figure 3-26). Because the individual mud classes overlap, the mid-points between the mean values were used to define the thresholds between the various classes (Table 3-3). T-tests of the mean velocities (P<0.1) for the individual mud classes show that the mean values are significantly different between all of the classes, and the velocity values within each class are also normally distributed. Substantial mud deposition takes place at velocities up to about 1.5 fps. Mud is present up to a velocity of about 2.2 fps. At velocities above 2.5 fps, there does not appear to be any mud deposition.

Table 3-3. Descriptive statistics for measured velocities (fps) for the individual subaqueous mud classes at Corn Lake.

Parameter	Class 2	Class 3	Class 4	Class 5	Class 6
Number of Values	28	14	32	14	41
Minimum	0	0.4	0.9	1.4	1.8
Median	0	0.7	1.8	2.5	3.2
Maximum	0.9	2.1	2.8	3.7	5.7
Mean	0.14	1.0	1.9	2.5	3.3
Standard Deviation	0.05	0.15	0.09	0.17	0.13
Range	0.9	1.7	1.9	2.3	3.9
Threshold Values	<0.6	0.6-1.5	1.5-2.2	2.2-2.9	>2.9

T-tests of the mean velocities (P<0.1) for the individual mud classes between the Clifton (Table 3-1) and Corn Lake (Table 3-3) sites show that with the exception of class 3, there are no statistically significant differences between the mean velocities for the individual mud classes at the 2 sites. There is no ready explanation for the differences in the mean velocities of the Class 3 sites between Clifton (1.3 fps) and Corn Lake (0.96 fps). However, the velocity data indicate that the mud dynamics at the two sites are very similar, and that the results of the more detailed studies at Clifton can be considered to be reasonably representative for the 15-MR.

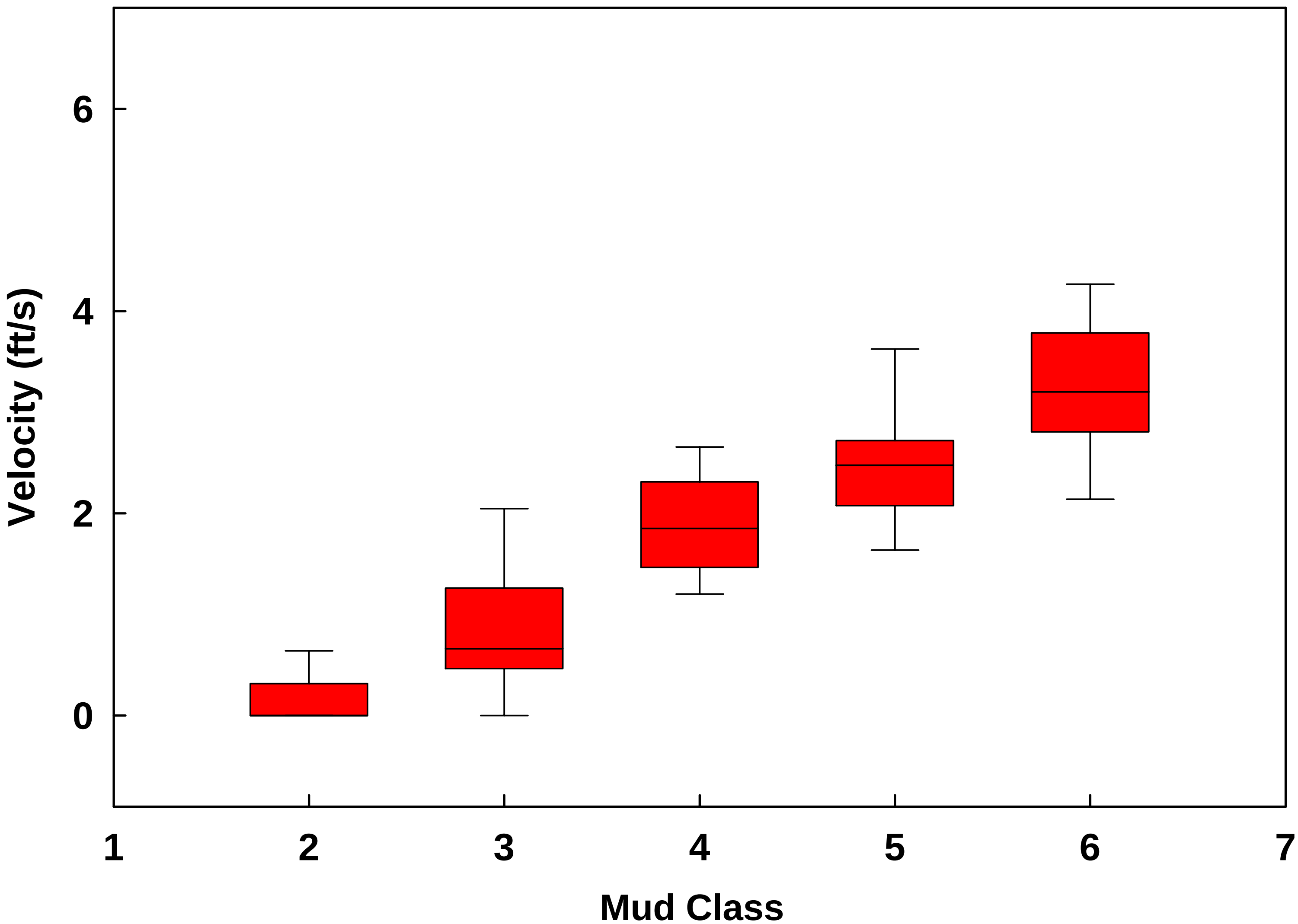


Figure 3-26. Box-and-whisker plots of the velocities for the individual subaqueous mud classes based on the measurements at Corn Lake.

3.1.5 Tracer Studies

Between the initial injection of tracers in October and the re-sampling in April, the injection sites were continuously inundated since the flows in the time period exceeded about 1,000 cfs. Discharges of up to about 1,800 cfs were recorded twice in the period between the initial spiking, in late October 2001 when the upstream Roller Dam was opened, and in mid-March 2002. Fine sediments were released when the dam was flushed, and there was a substantial flush of sediment from Plateau Creek into the Colorado River in late March. Additional mud was deposited at the Clifton site. Based on the turbidity record, there were a number of other higher turbidity events during the winter period as well (Figure 3-17). To determine whether the tracers had been either leached or the mud had been mobilized, the injection sites were precisely relocated with the Total Station and sampled in April, 2002 (Figure 2-10). Two control samples were also collected upstream of the bar. All the samples were analyzed for the two metals. Results of the analyses indicated that the nickel tracer was still in place, but at three of the silver injected sites there was no detection (Table 3-4). Subsequent sampling on June 27, 2002, indicated that the silver was still present at all of the injected sites, and therefore, it has been concluded that the sampling depth in April was probably insufficient because of additional sediment deposition at these locations.

All the injected deposits were still present following the runoff period in 2002 (Table 3-4). However, given the very low magnitude of the snowmelt runoff in which the peak discharge was about 2,800 cfs at the Palisade gage; it is not surprising that the mud was not mobilized. The results of the 2-D modeling of the site indicate that threshold conditions for mud mobilization (conditions that are required to result in generalized mobilization of bed materials, mud and tracers) are not reached until about 4,800 cfs at this location (see Section 3.1.9 for further discussion). Therefore, the tracer study was unable to provide resolution of the question of mud remobilization. Resampling will be required when the discharge has exceeded 4,800 cfs.

Table 3-4. Summary of results of chemical analyses (ppm) for Clifton site.

Site	Analyzed Metal	Background [1]	April 9, 2002 Sampling	June 27, 2002 Sampling
1	Nickel	11.7	168	145
4	Nickel	11.9	114	45.5
6	Nickel	11.9	171	138
8	Nickel	12.4	9.37	1130
10	Nickel	12.7	93	450
2	Silver	ND	3	0.8
3	Silver	ND	ND	56.3
5	Silver	ND	ND	21
7	Silver	ND	4.4	50.5
9	Silver	ND	ND	73.5
Control 1 (2 samples)	Nickel		3.52, 9.38	9.07, 6.36
Control 2 (2 samples)	Silver		ND, ND	ND, ND

[1] Detection limit for Ni is 1 ppm, and Ag is 0.5 ppm.

3.1.6 Suspended Sediment

The USGS collected suspended-sediment samples at the Cameo gage between 1982 and 1998. The frequency of sampling varied over the period of record as shown by the example of WY 1986, but ranged from monthly to weekly (Figure 3-27). The pattern of the suspended-sediment concentrations is very similar to the Clifton site where the suspended-sediment concentrations are high on the early part of the rising limb of the hydrograph, but decline rapidly as discharge increases. With the exception of a single sample, the post-runoff record at the Cameo gage does not reflect the effects of runoff generated by summer thunderstorms because of the sampling frequency. There were a number of summer thunderstorms in the Grand Junction and Rifle areas in the post-runoff period in WY 1986, but these did not coincide with the suspended-sediment sampling at the Cameo gage (Figure 3-27). As a result, it is likely that the Cameo gage record does not fully represent the post-runoff suspended-sediment regime.

Individual suspended-sediment measurements are segregated into the sand and finer fractions on Figure 3-27 for further analysis. These data show that during the snowmelt runoff period there is a higher sand content in the suspended sediment sample, and during the remainder of the year the suspended sediment samples are primarily composed of silts and clays. The suspended-sediment rating curve for the entire period of record at the Cameo gage shows a weak relationship between discharge and suspended-sediment concentration ($R^2 = 0.3$) (Figure 3-28).

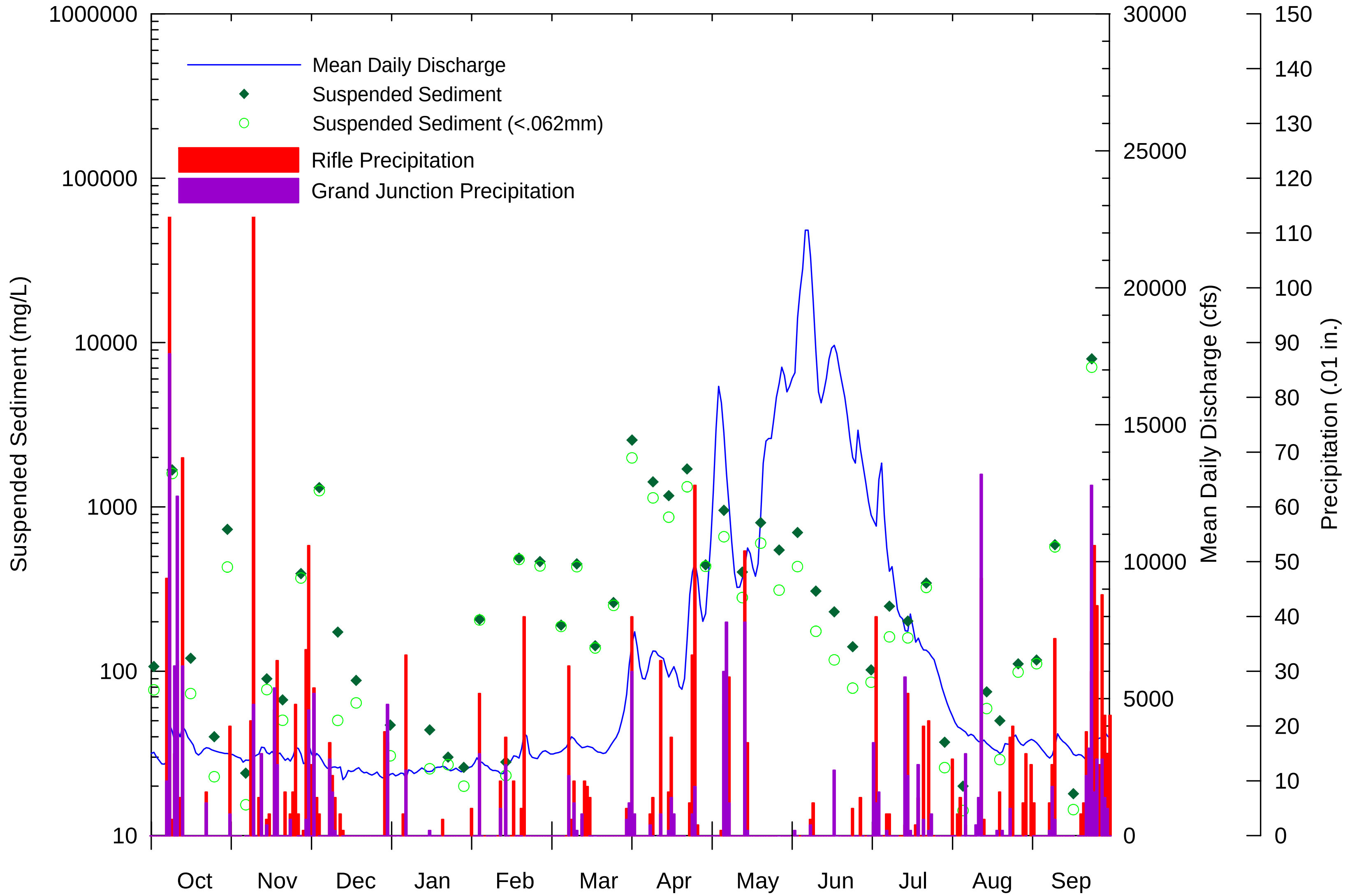


Figure 3-27. Annual hydrograph for WY 1986 at the Cameo gage showing the frequency of suspended-sediment measurements, the resulting suspended-sediment concentrations, and the recorded precipitation at Grand Junction and Rifle.

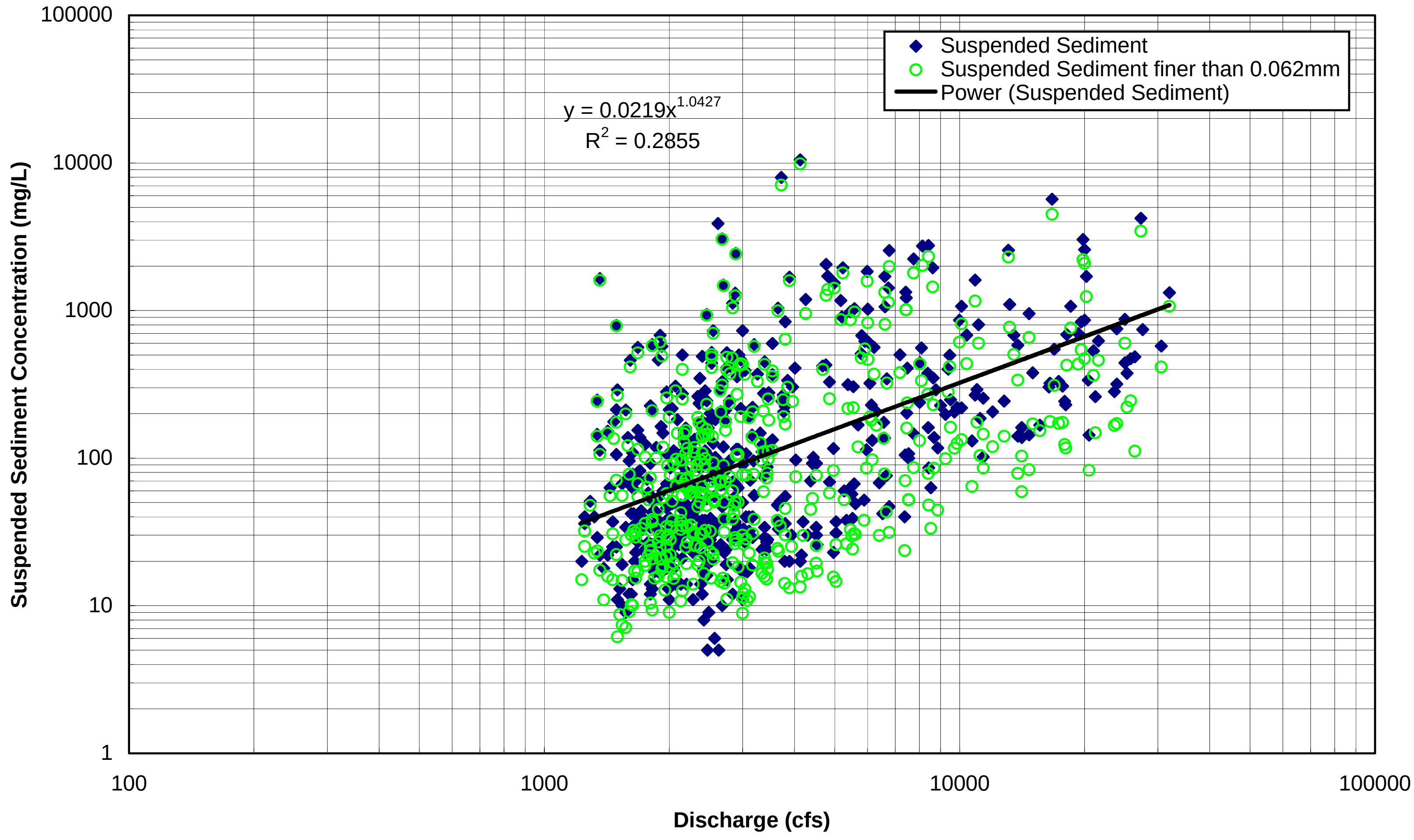


Figure 3-28. Suspended-sediment rating curve for the USGS Cameo gage (1982-1998).

The suspended-sediment data were segregated into three periods for seasonal analysis (Figure 3-29): 1) from October 1 to the commencement of the snowmelt runoff, 2) during the runoff period, and 3) the post-runoff period. In general, higher concentrations are associated with the snowmelt runoff period, but the highest values are found in the pre- and post-runoff periods. Analysis of the sand fraction by seasonal time periods (Figure 3-30) shows that the highest sand contents occur in the runoff period (average of 28 percent of the sample), and tend to be lower in the pre-runoff period (average 18 percent) and post-runoff period (average 12 percent). The sand-fraction data indicate that in the lower flow periods, the suspended-sediment load is dominated by the silt-and-clay fractions that are primarily responsible for the high turbidity values (Kirk 1988; Davies-Colley et al. 1993).

Suspended-sediment data for the Cameo gage period of record, segregated by the three time periods, was compared to the suspended-sediment data collected at the Clifton site (Figure 3-31). The suspended sediment concentration data were also separated into two groups based on a threshold discharge of greater or lesser than 1,500 cfs. The power functions for the two data sets show clearly that the suspended sediment concentrations at the lower flows are higher than those of the higher flows. The Clifton suspended-sediment concentrations are very similar to those from the Cameo gage at discharges above 1,500cfs. However, at the lower discharges, the suspended-sediment concentrations at Clifton tend to be higher than those measured at Cameo. The reason for the higher concentrations at the Clifton site is that in the post-runoff period the suspended- sediment samples were collected during thunderstorm runoff-generated events during WY 2001 and WY2002, and during the runoff season in WY 2002 when the peak flows were very low and there was a considerable in-channel source of sediment available for remobilization under relatively low-flow conditions.

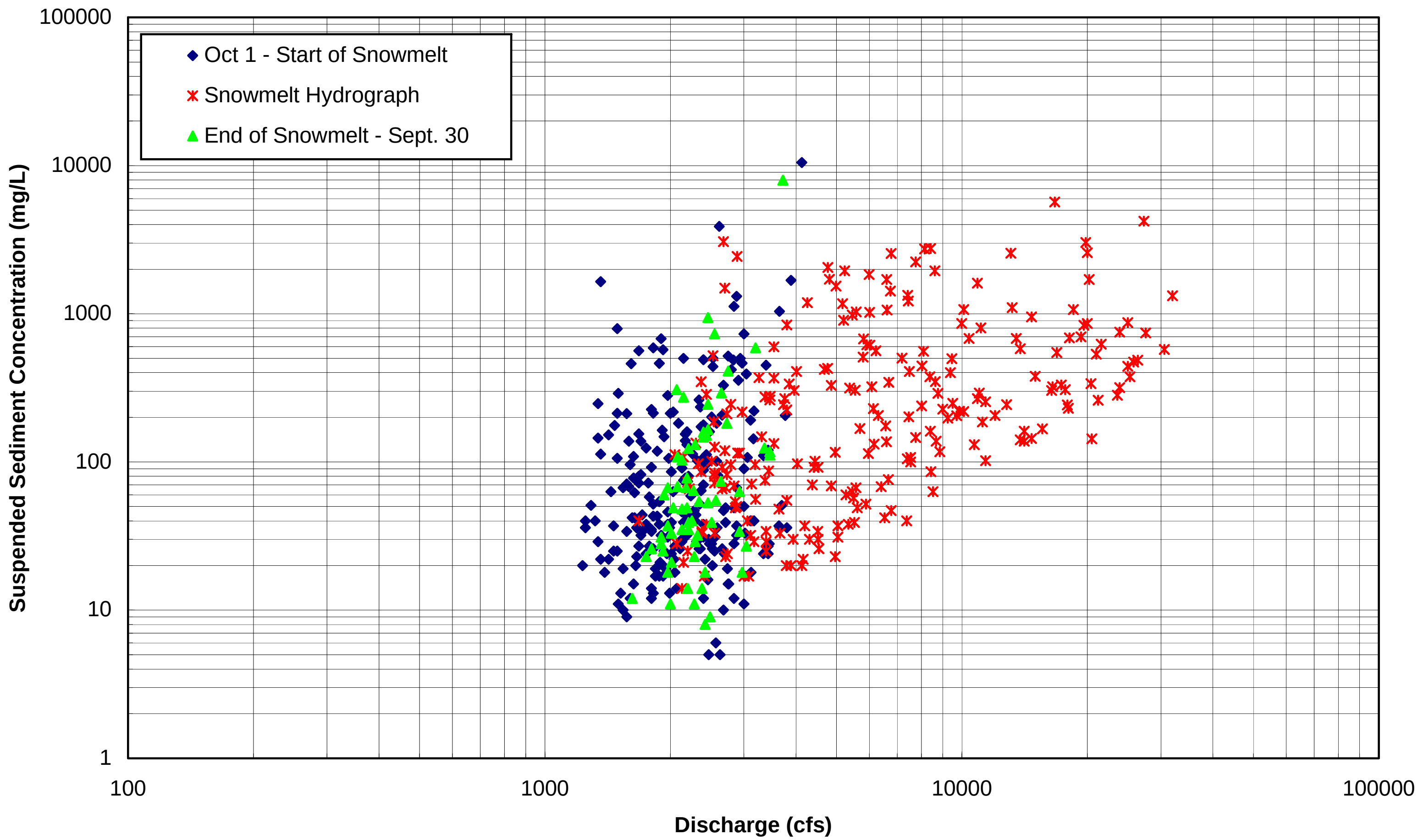


Figure 3-29. Suspended-sediment record at the USGS Cameo gage sorted by season (1982-1998).

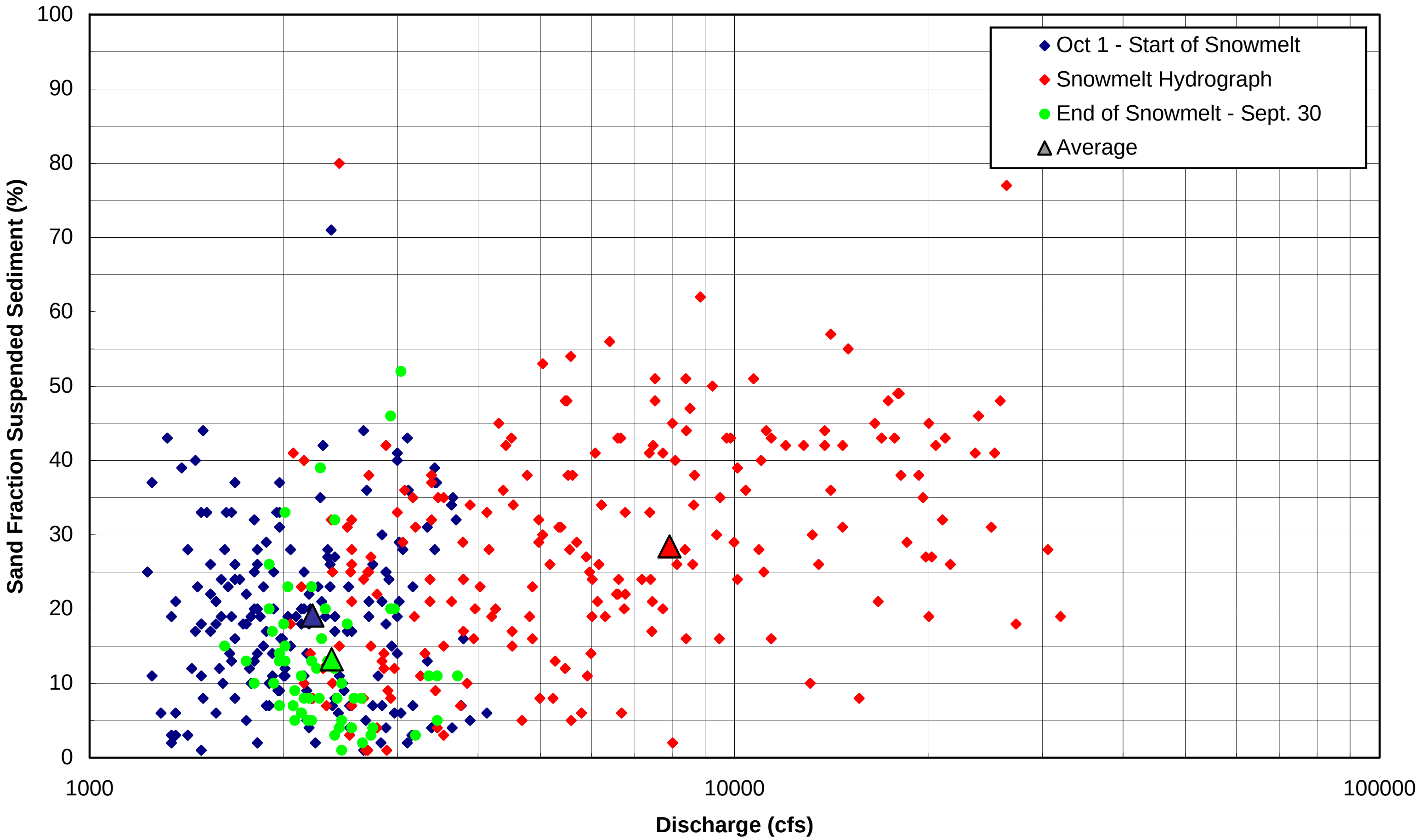


Figure 3-30. The sand fraction of the suspended-sediment record at the USGS Cameo gage sorted by season (1982-1998).

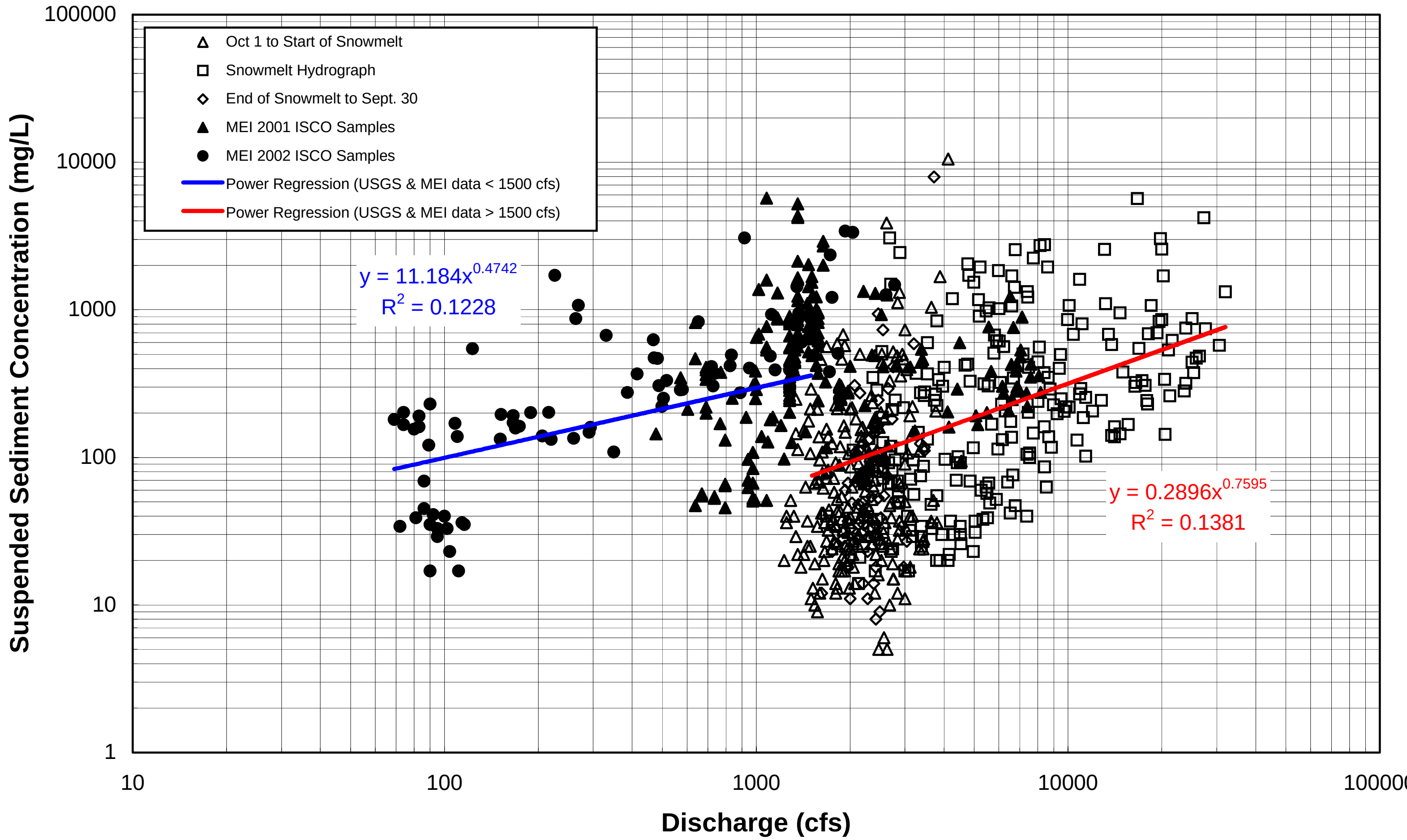


Figure 3-31. Suspended-sediment record at USGS Cameo gage (1982-1998) with Clifton data for WY 2001 and WY 2002 added.

3.1.7 Numerical Modeling

The 2-D model generated water depth, velocity, and shear stress data for discharges of 800, 1400, 2000, 4800, 11,340, 15,000 and 25,000 cfs (See appendix). At 800 cfs, the mid-channel bar and a small bar at the head of the reach on the left side of the channel are subaerially exposed, and flow depths throughout the site are less than 5 feet (Figure 3-32). At 4,800 cfs, the entire reach is inundated. Depths in the runs are on the order of 4 to 6 feet, but they are shallow in the riffles (<3 feet). At 15,000 cfs, depths in the runs are on the order of 10 feet, and riffle depths are on the order of 4 to 5 feet. At 25,000 cfs, run depths exceed 12 feet and the riffle depths are on the order of 5 to 6 feet (Figure 3-33). At this discharge the flow depth over the mid-channel bar is approximately 5 feet.

At a discharge of 800 cfs, velocities in riffles are less than 5 fps, but the bulk of the site has velocities in the range of 0-3 fps (Figure 3-34), which is well within the identified range for mud deposition. Low velocities within the range for mud deposition are also present in much of the reach at a discharge of 2,000 cfs. At 4,800 cfs, velocities exceed 4 fps in most of the reach, except on the margins of the channel and the mid-channel bar. Within the lower velocity zones, deposited mud would be expected to be present. At a discharge of 25,000 cfs, except for very small channel margin areas, velocities exceed 4 fps throughout the site, and therefore, other than in the low velocity, narrow marginal areas, mud deposition would not be expected (Figure 3-35). At higher discharges, any areas of deposition would be located on the channel banks, and for most of the year these areas would not be inundated and would not, therefore, be providing subaqueous habitat.

3.1.8 Incipient Motion

Even at a low discharge of 800 cfs, there are locations in the riffles where incipient motion thresholds are exceeded (Figure 3-36). Field observations tend to support the results of the modeling in these reaches. However, for the majority of the site the shear stress is very low. With an increase in discharge to 1,100 cfs, there is an expansion of those areas where the grain shear exceeds a value of 1, but these are still restricted to the riffles. At a discharge of 1,400 cfs, which is near the upper range of discharges that occur in the 15-MR in the post-runoff period,

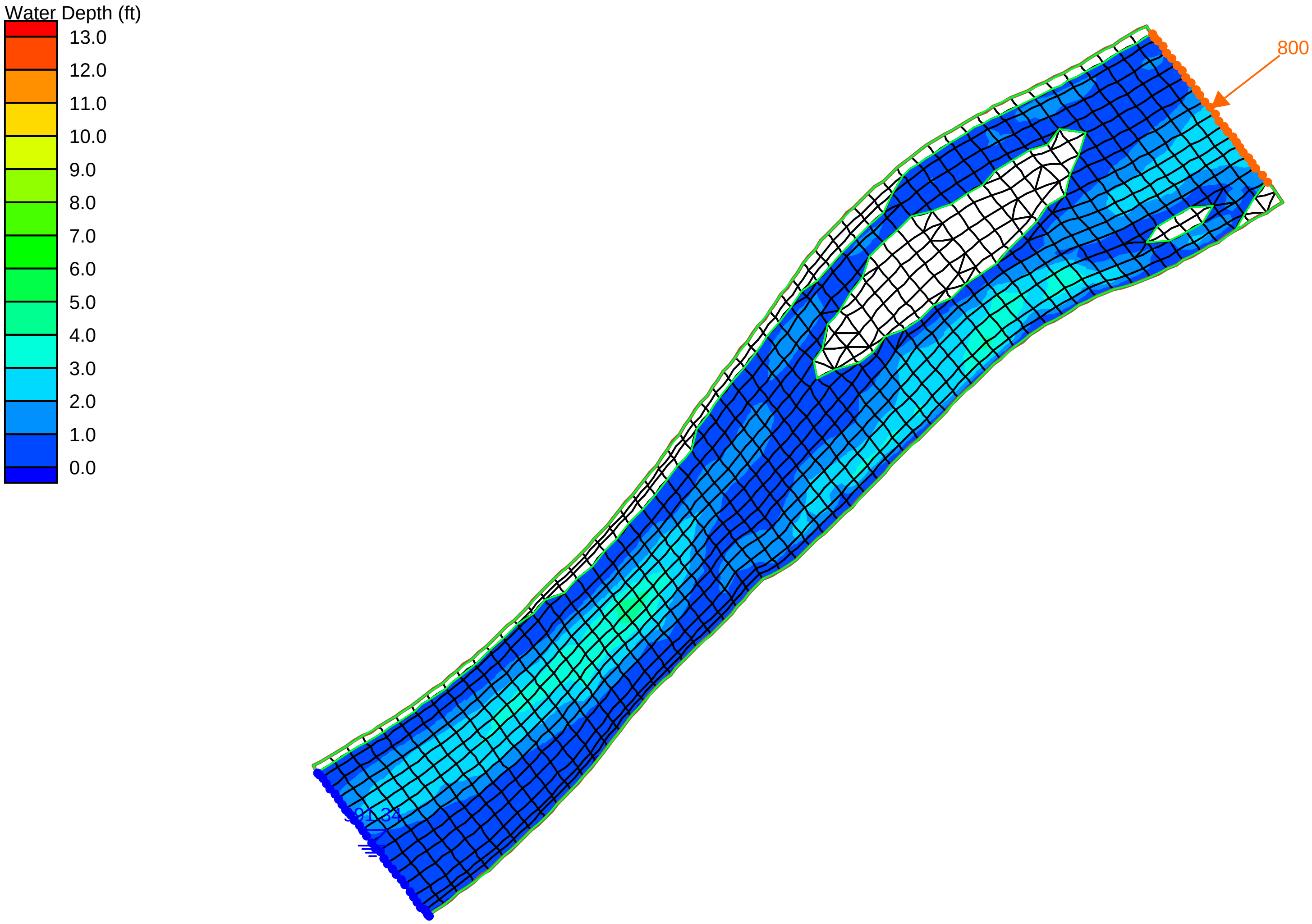


Figure 3-32. Color-gradient plot of predicted water depth from 2-D model of Clifton site at a discharge of 800 cfs.

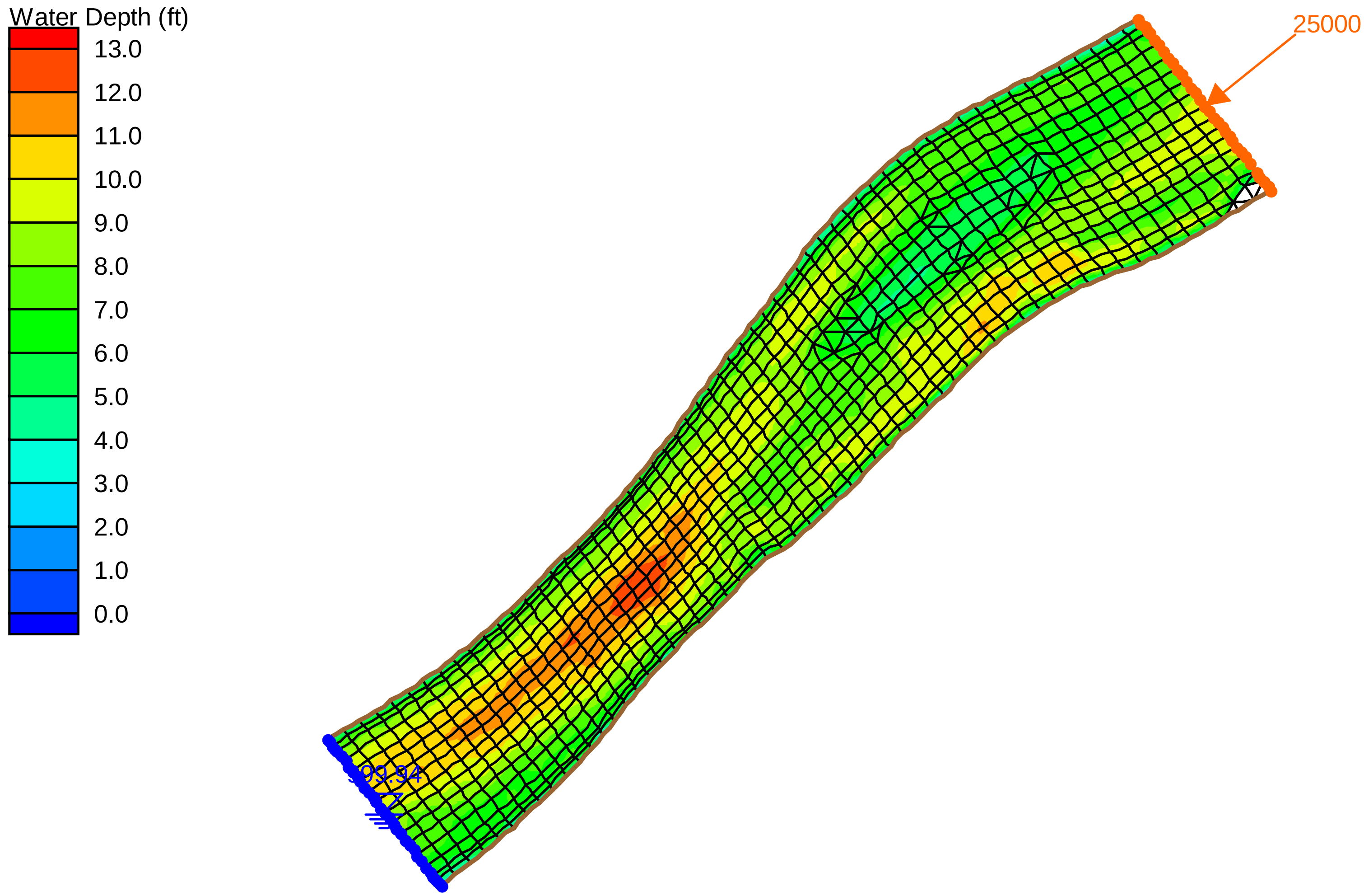


Figure 3-33. Color-gradient plot of predicted water depth from 2-D model of Clifton site at a discharge of 25,000 cfs.

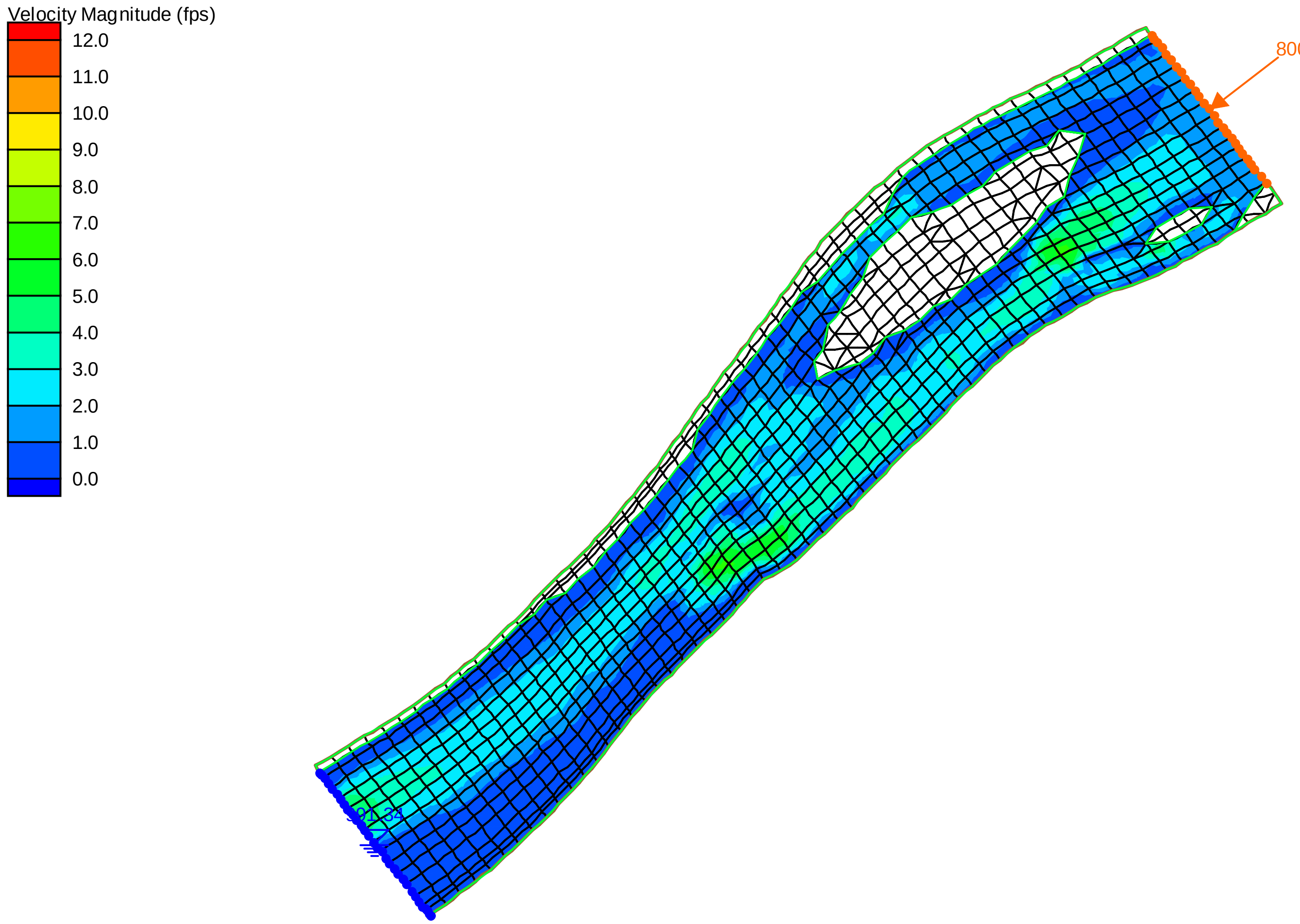


Figure 3-34. Color-gradient plot of predicted velocity from 2-D model of Clifton site at a discharge of 800 cfs.

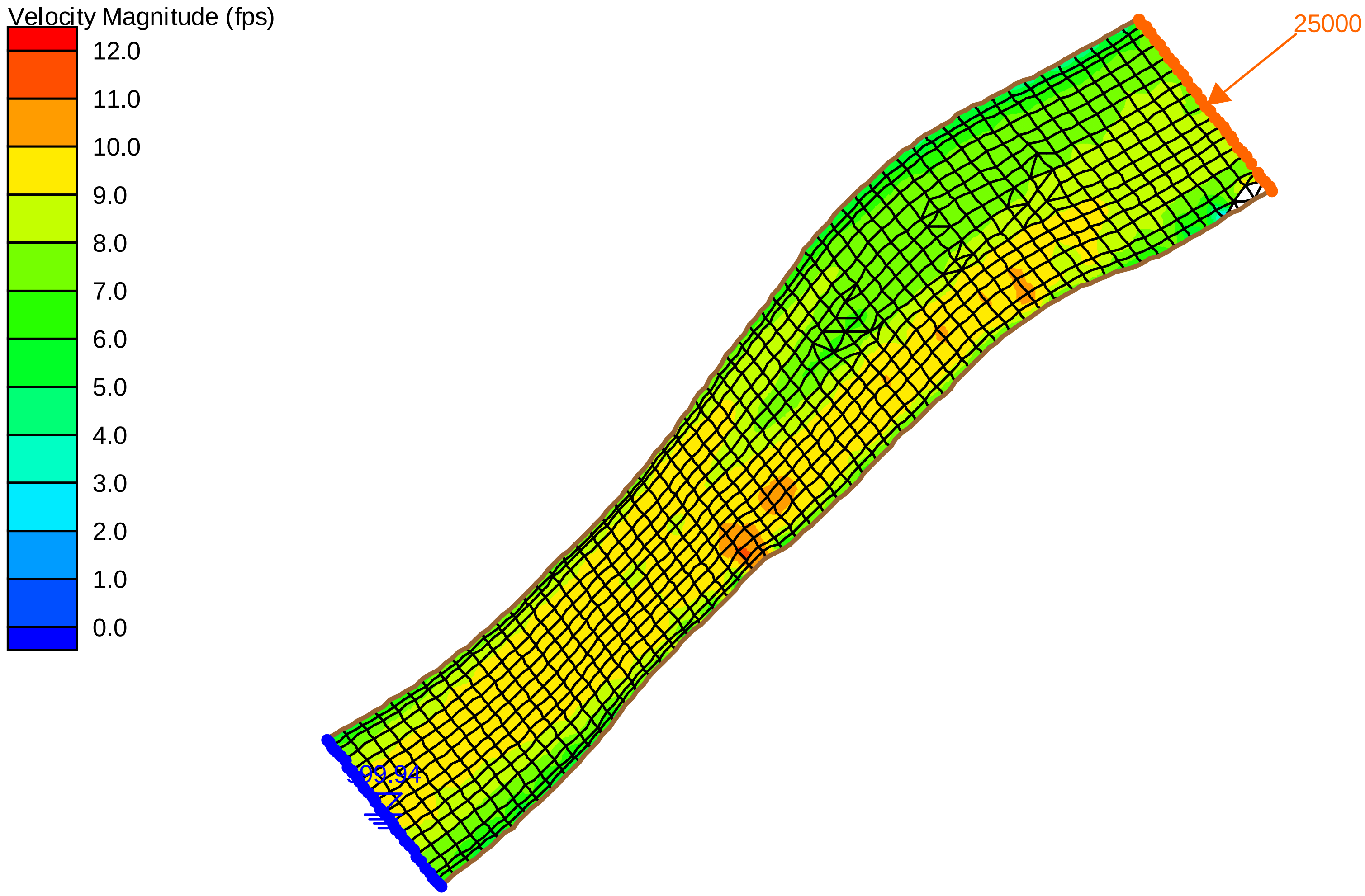


Figure 3-35. Color-gradient plot of predicted velocity from 2-D model of Clifton site at a discharge of 25,000 cfs.

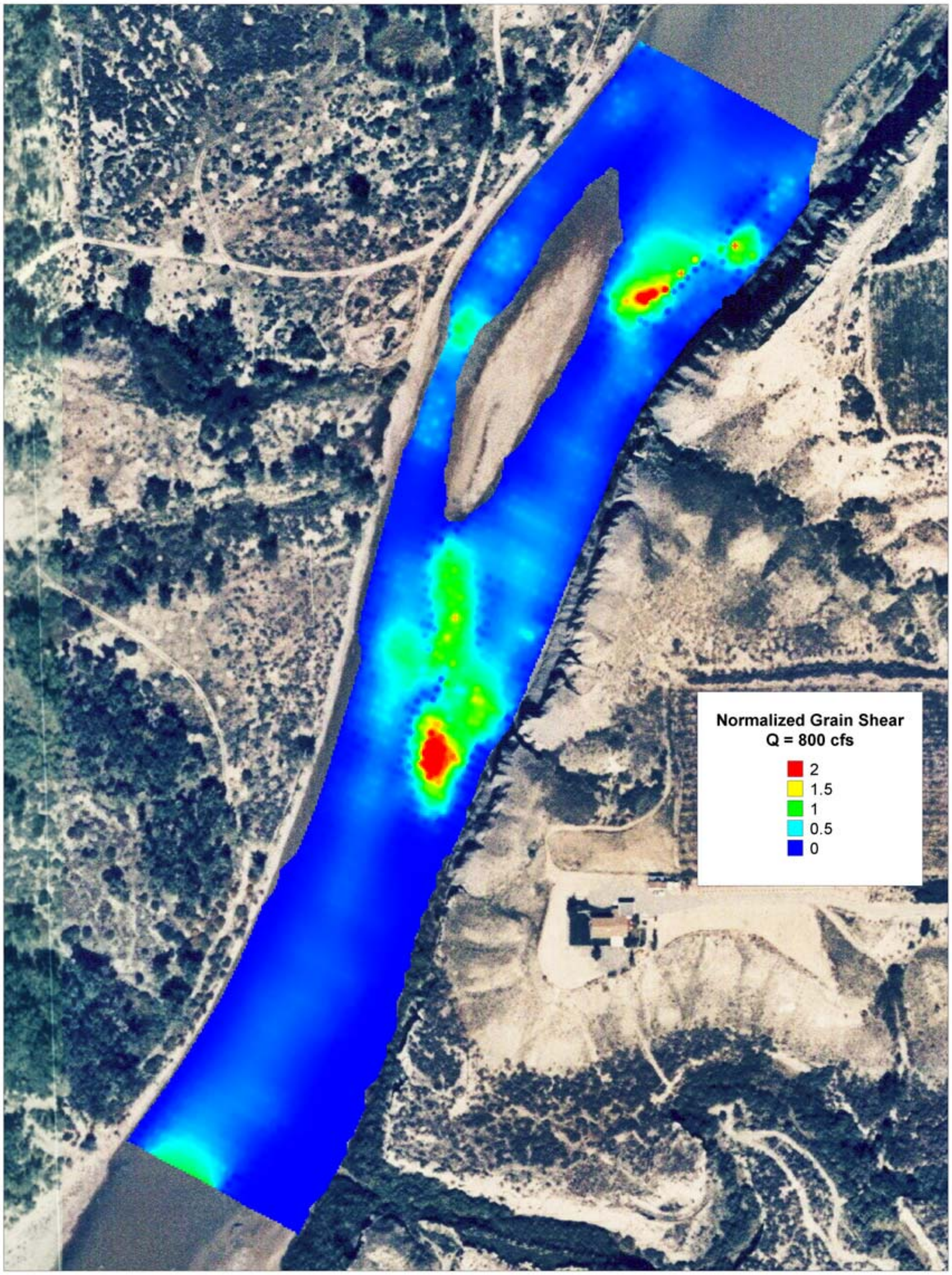


Figure 3-36. Color-gradient plot of computed normalized grain shear developed from the 2-D model of the Clifton site at a discharge of 800 cfs.

the only areas where incipient conditions occur are the riffles. With increases in discharge up to 4,800 cfs the model results show that the majority of the reach upstream of the large cross-channel riffle is at a condition approaching incipient motion of the bed material (Figure 3-37). The areas where the shear stresses are low are restricted to the bar and channel margins, and the lower run. At 8,000 cfs, the riffles begin to drown out, but a considerable part of the upper part of the reach is at, or near, incipient conditions. At 11,340 cfs the bed material in the lower run is still below incipient conditions. At a discharge of 15,000 cfs, incipient conditions are present at most locations in the reach. Substantial sediment transport takes place throughout the reach at discharges above 20,000 cfs (Figures 3-38). The results of the incipient motion analysis indicate that incipient conditions are present in the riffles even at low discharges, because the local energy gradients are steepest under these conditions (Harvey et al. 1993; Mussetter et al. 2001). The riffles begin to drown out at a discharge of about 8,000 cfs. Normalized shear stresses approaching a value of 1 are found throughout the site at a discharge of between 13,000 and 15,000 cfs, which is somewhat higher discharge than that reported by Pitlick et al. (1999). General transport of the bed material occurs at discharges between 20,000 cfs and 25,000 cfs, which is within the range (22,000 cfs) reported by Pitlick et al. (1999).

3.1.9 Fine Sediment (Mud) Dynamics

The Darcy-Weisbach formula (Equation 12) and output from the 2-D model for the Clifton reach were used to compute shear stress for a range of discharges from 800 cfs to 4,800 cfs. The threshold values between the mud classes that are shown on the plots correspond to those in Table 3-2. At a discharge of 800 cfs, provided that mud producing events have occurred, substantial mud deposits should be present in the blue and green areas where the shear stress is less than 0.03 lb/ft^2 (Figure 3-39). This was corroborated by field observations on October 16, 2001, when the mud tracer injection was done (Figure 2-10). On the right side of cross section 2 (run) where the biological sampling was conducted, mud class 2 was present, whereas on the right side of Cross Section 5 (riffle) where biological sampling was also done, classes 3 and 4 were present.

A discharge of 1,100 cfs is the discharge that is equaled or exceeded about 85 percent of the time and is typical of the flows that occur in the post-runoff period when the mud deposition is most likely to occur as a result of mud supply by the summer thunderstorms. Comparison of the

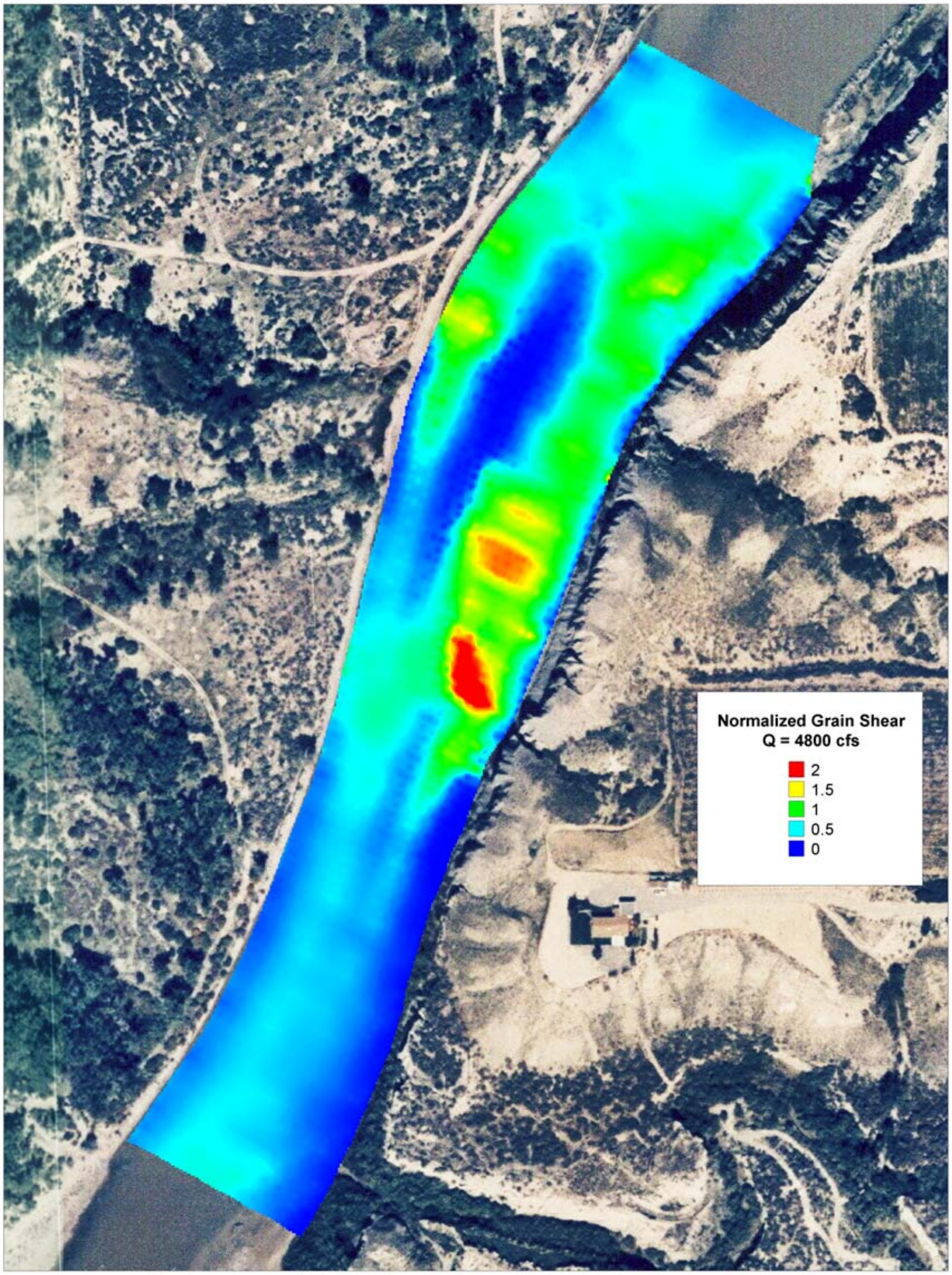


Figure 3-37. Color-gradient plot of computed normalized grain shear developed from the 2-D model the Clifton site at a discharge of 4,800 cfs.

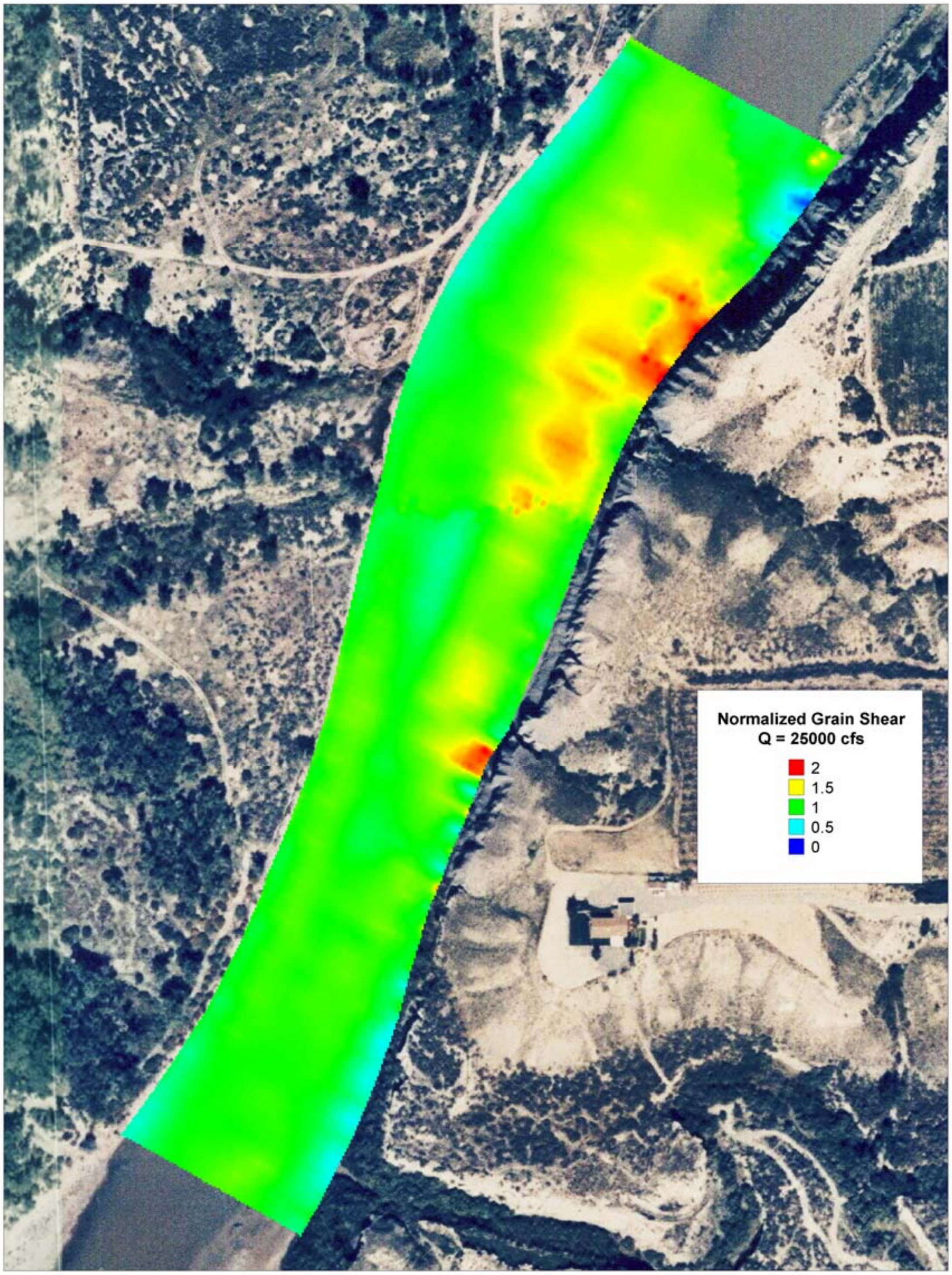


Figure 3-38. Color-gradient plot of computed normalized grain shear developed from the 2-D model of the Clifton site at a discharge of 25,000 cfs.

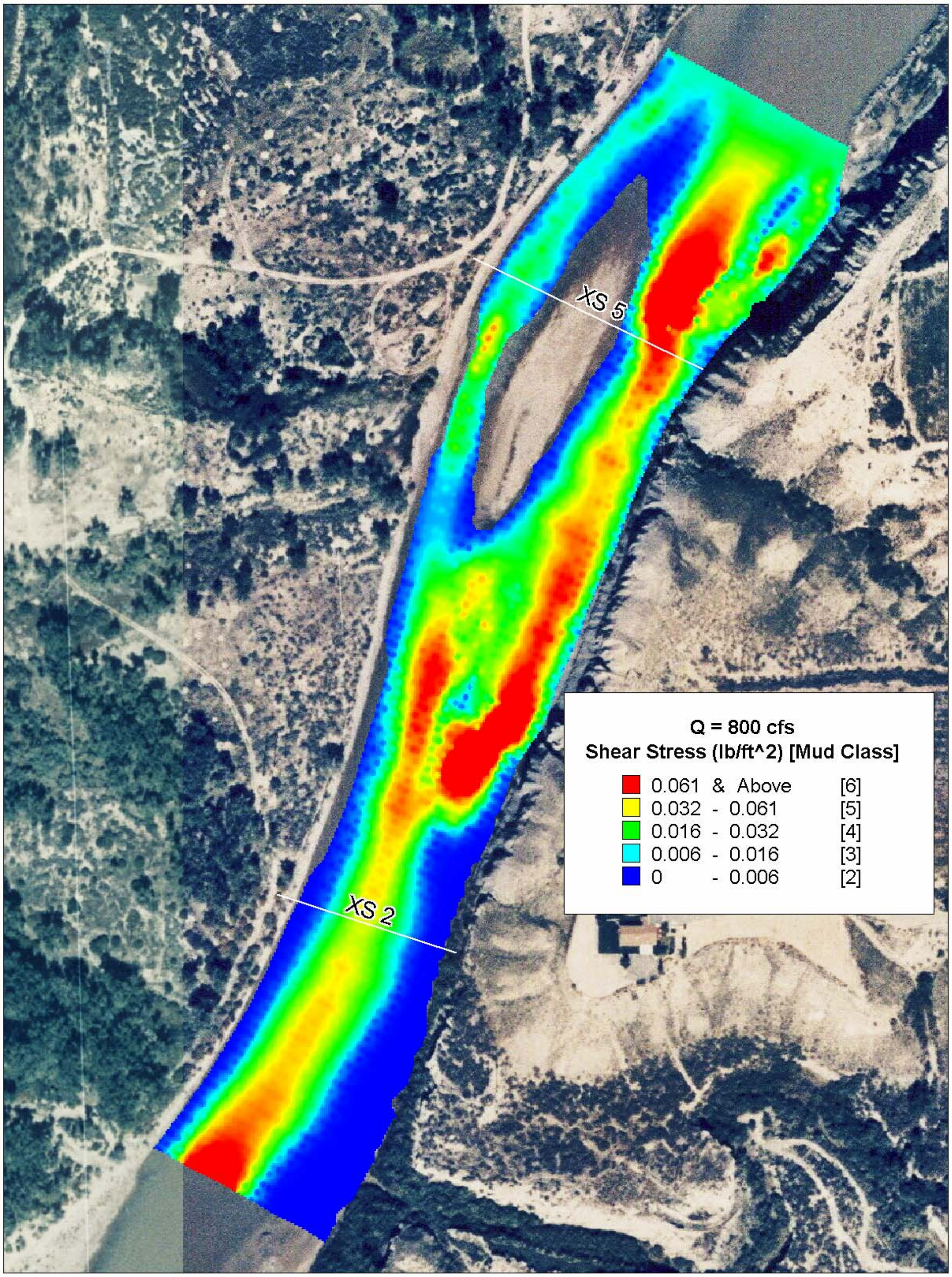


Figure 3-39. Color-gradient plot of computed shear stress developed from the 2-D model of the Clifton site at a discharge of 800 cfs.

predicted spatial distribution of the mud classes for 1100 cfs (Figure 3-40) with the field measured boundaries (Figure 3-23), indicates that the 2-D model output and the identified shear stress thresholds between the individual classes replicates the field situation reasonably well. The basic patterns shown on Figure 3-23 are all replicated in Figure 3-40, but the model tends to overestimate the shear, and hence underestimate the amount of mud in the region of the cross-channel riffle. Throughout the rest of the site the model replicates the field observations well. On the right side of Cross Section 2 where the biological sampling was conducted, mud class 2 was present, whereas on the right side of cross section 5 where biological sampling was conducted, mud classes 3 and 4 were present.

A discharge of 1,400 cfs was present at the site when the mud resampling was conducted on April 9, 2002. The observed spatial distribution of the mud deposits at the head of the mid-channel bar, as well as on the bar margins, was very similar to that shown on Figure 3-41. Some mud (class 4) was observed along the right side of Cross Section 5 where the biological sampling was conducted, and significant mud (class 2) deposits were present along the right margin of Cross Section 2. At a discharge of 2,000 cfs, which is the discharge that is equaled or exceeded about 45 percent of the time, the model output indicates that large areas of the site are at shear stresses above those where substantial amounts of mud are present (> 0.03 lb/ft^2) (Figure 3-42). Mud deposits should be present only along the margins of the mid-channel bar and the margins of the channel, primarily in the lower half of the site. On the right side of cross section 2, mud classes 2 and 3 are predicted to be present, whereas on the right side of Cross Section 5, mud classes 4 and 5 are predicted to be present.

A discharge of 4,800 cfs is currently equaled or exceeded about 15 percent of the time, but was equaled or exceeded about 22 percent of the time before 1950. With the exception of the areas around the mid-channel bar and along the left bank of the channel in the downstream part of the reach, the shear stresses exceed 0.03 lb/ft^2, and therefore, very little mud can be expected to be present at the site (Figure 3-43). The shear stress distribution at the head of the mid-channel bar indicates that a higher discharge will be required to mobilize all of the injected mud deposits since the shear stress values at those locations were still less than 0.03 lb/ft^2. On the right side of Cross Section 2, mud classes 4 and 5 were predicted to be present, whereas on the right side of Cross Section 5, mud class 6 was predicted to be present.

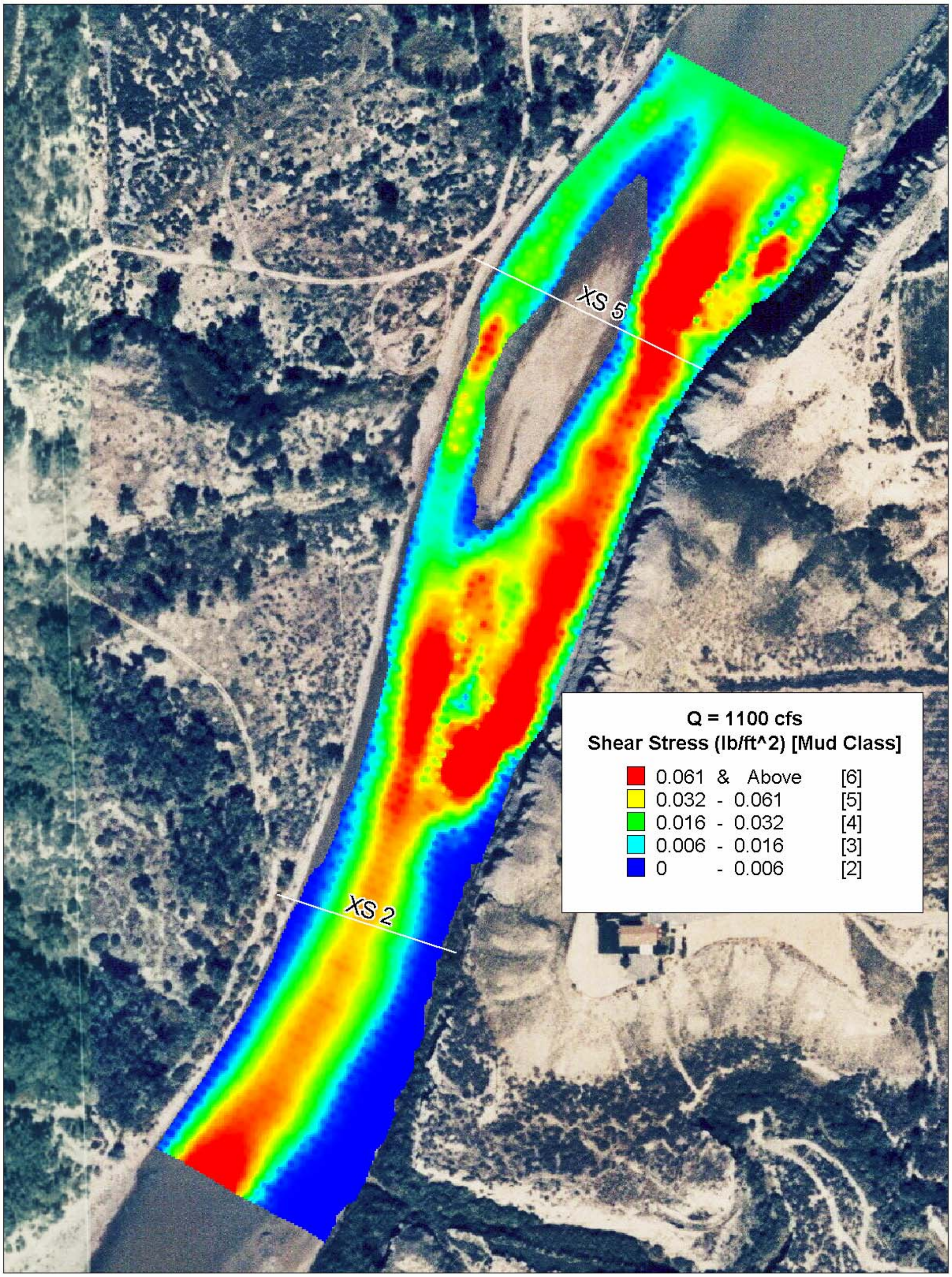


Figure 3-40. Color-gradient plot of computed shear stress developed from the 2-D model of the Clifton site at a discharge of 1,100 cfs.

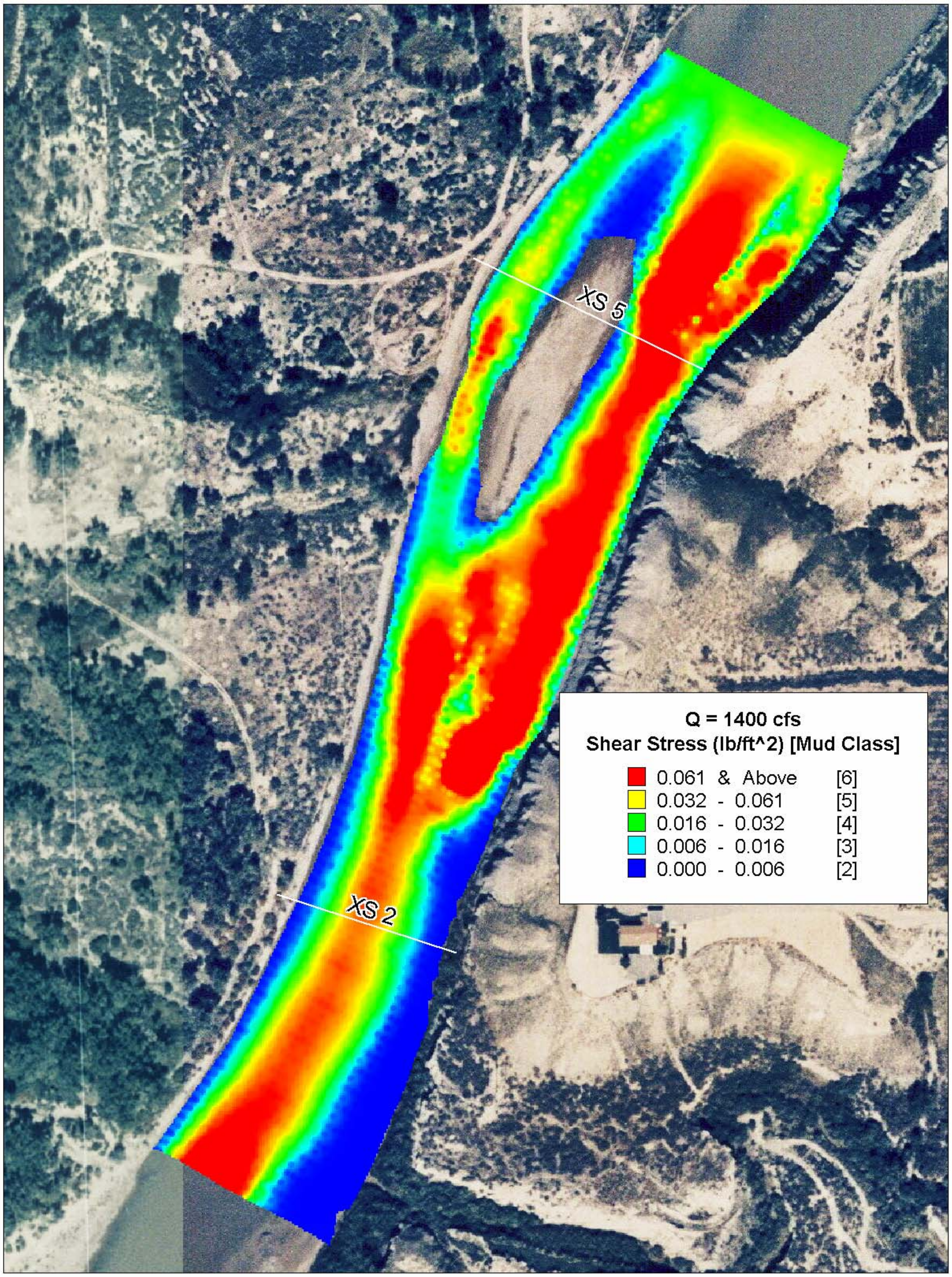


Figure 3-41. Color-gradient plot of computed shear stress developed from the 2-D model of the Clifton site at a discharge of 1,400 cfs.

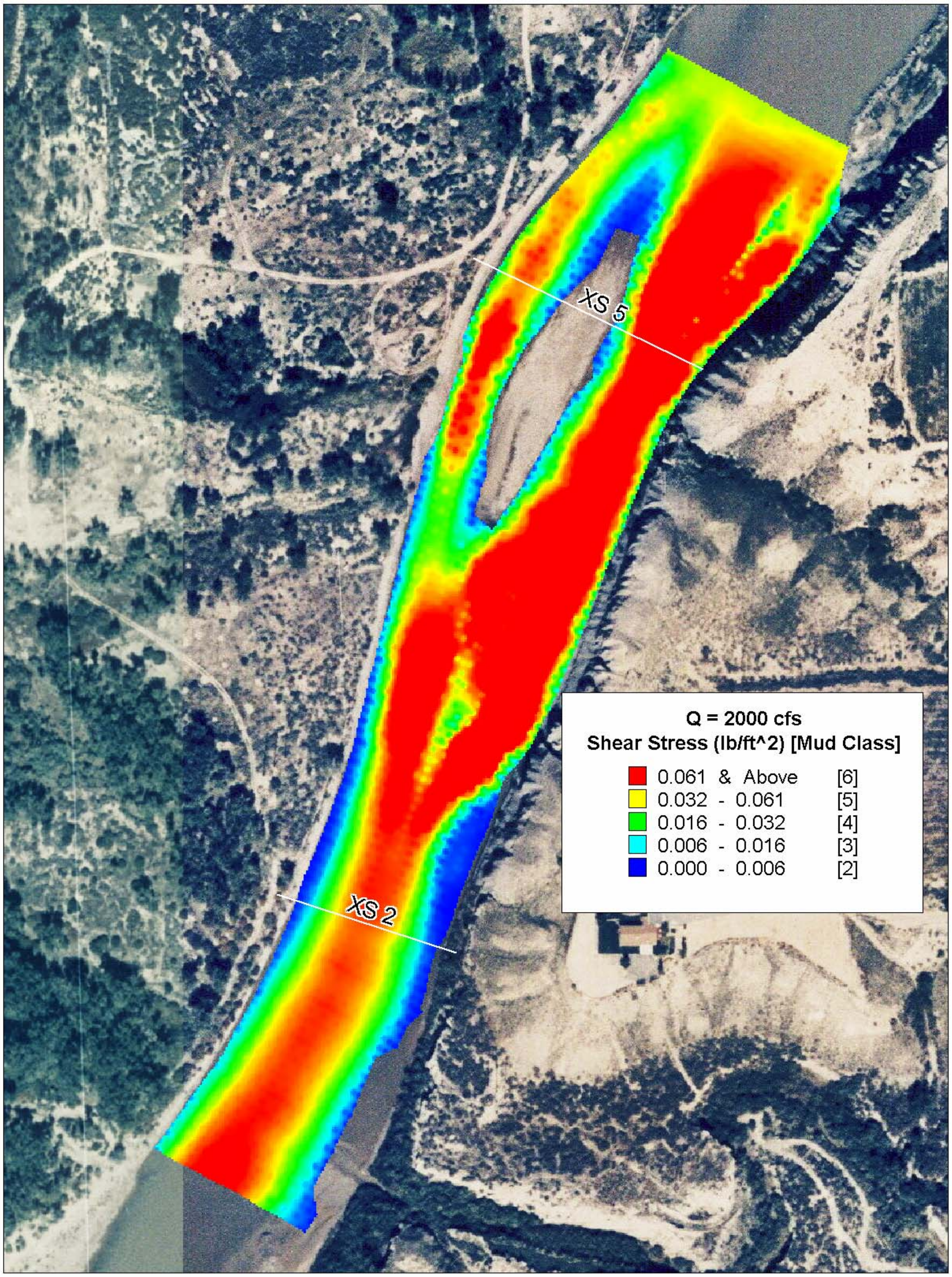


Figure 3-42. Color-gradient plot of computed shear stress developed from the 2-D model of the Clifton site at a discharge of 2,000 cfs.

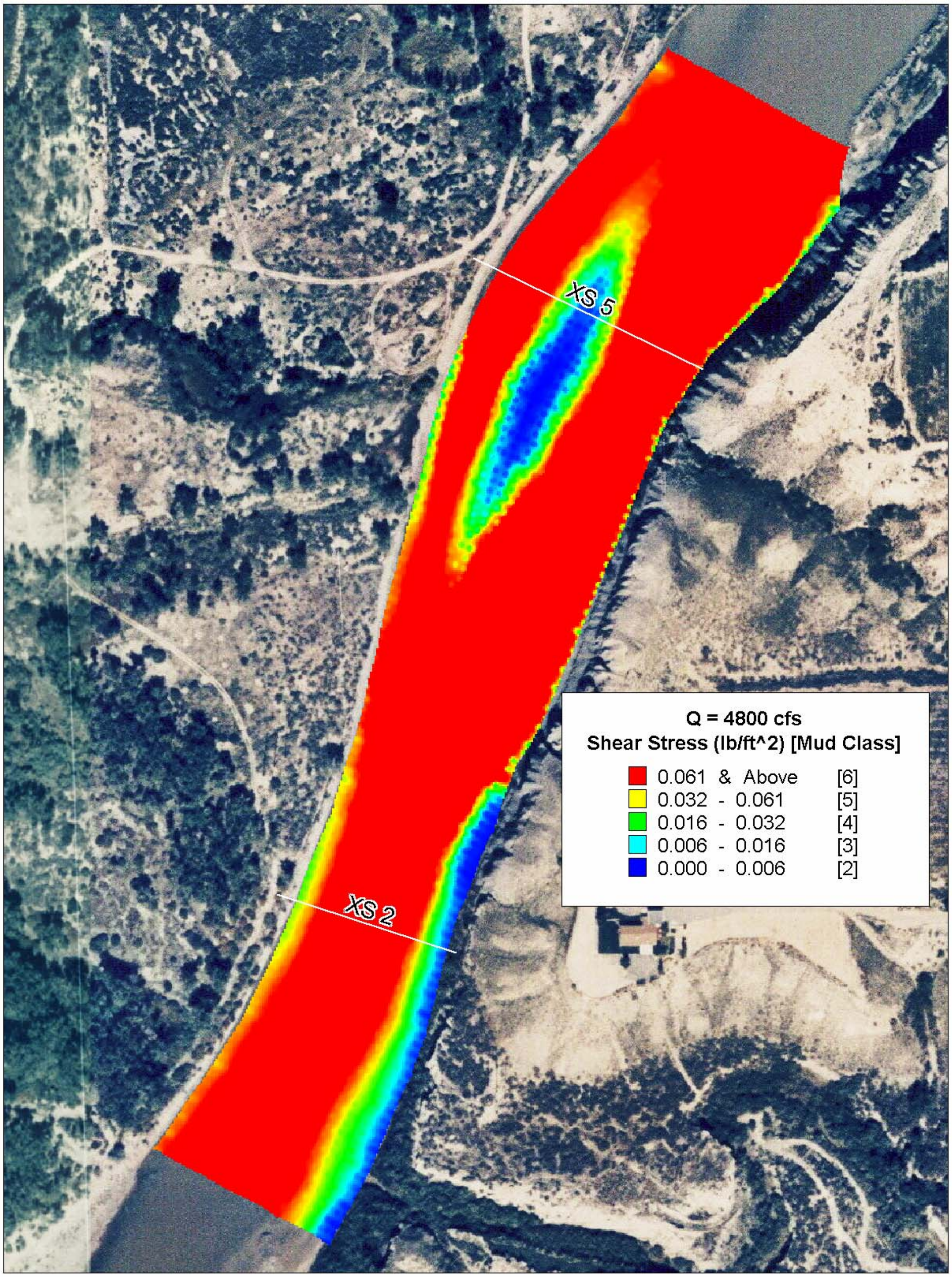


Figure 3-43. Color-gradient plot of computed shear stress developed from the 2-D model of the Clifton site at a discharge of 4,800 cfs.

3.2 Biological Investigations

3.2.1 Physical Properties

Specific physical components of the system were monitored in order to make comparisons with trends in biological communities (See Section 3.1). Discharge (and the corresponding point velocity) and turbidity are two of the primary variables believed to influence biological processes. A comparison of discharge data from 1999 through 2003 illustrates some obvious differences between years (Figure 3-17). The most general differences include a shorter period of runoff and overall lower midsummer flows during the year 2000, and the relatively low peak flow and base flows during 2002.

Turbidity was also highly variable between sampling seasons (Figure 3-16). The highest peaks in turbidity typically occurred in mid to late summer as a result of thunderstorm events that caused erosion in small tributaries and mobilization of channel margin sediments. In most cases peaks in turbidity were associated with summer rain events.

As this investigation progressed it appeared that biological communities were responding to specific physical processes that were independent of annual peak flow events. For example, benthic macroinvertebrates aggregated in areas where preferred habitat and substrate was made available due to adequate current velocities. At the onset of the year 2000 sampling season, mean flow velocities were measured at the location of each periphyton and macroinvertebrate sample at the Clifton site (Figure 3-44). This procedure was also used at the synoptic sites during the 2001 season (Figure 3-45). The velocity data were entirely dependent on sample location. The data were used to verify differences between habitats at each riffle/run complex, not to indicate seasonal changes or changes in discharge.

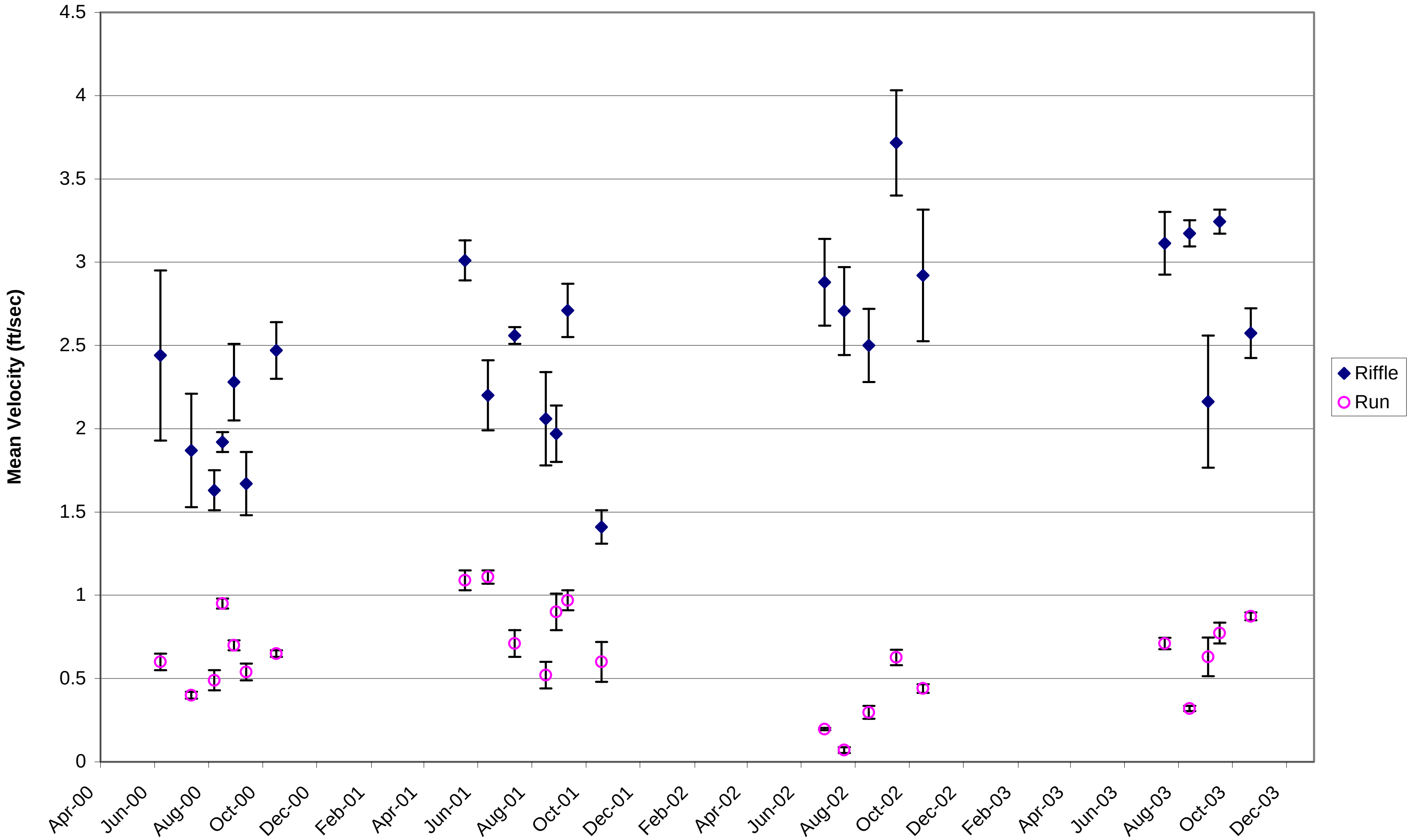
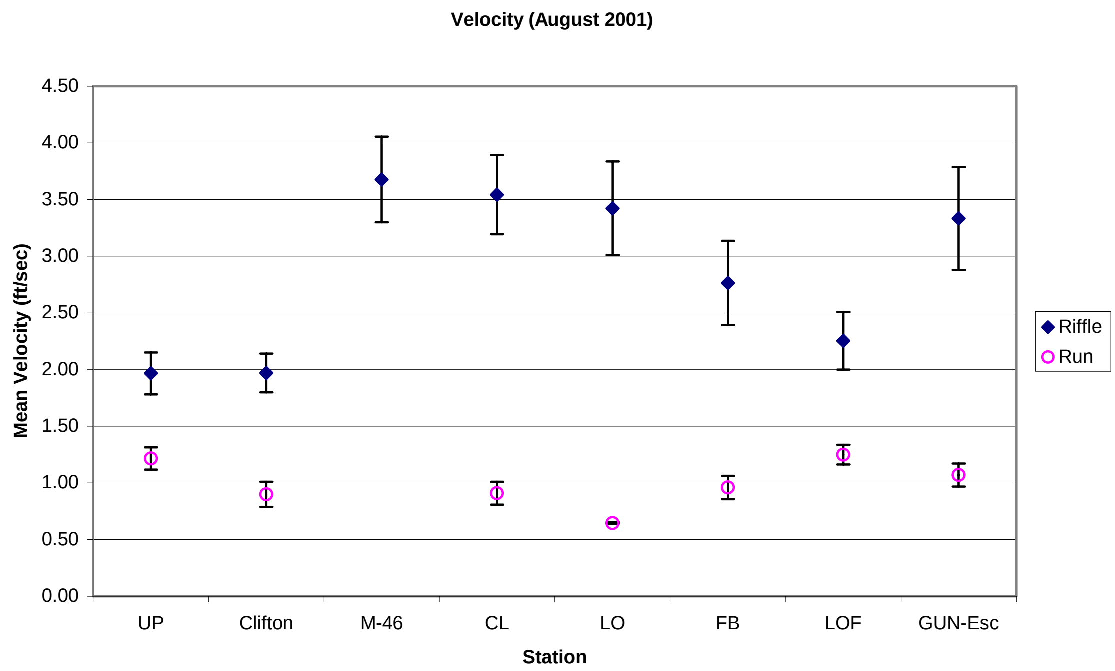


Figure 3-44. A comparison of mean flow velocity (± 1 standard error) at specific sample locations at the Clifton site in the 15-MR of the Colorado River, Colorado.



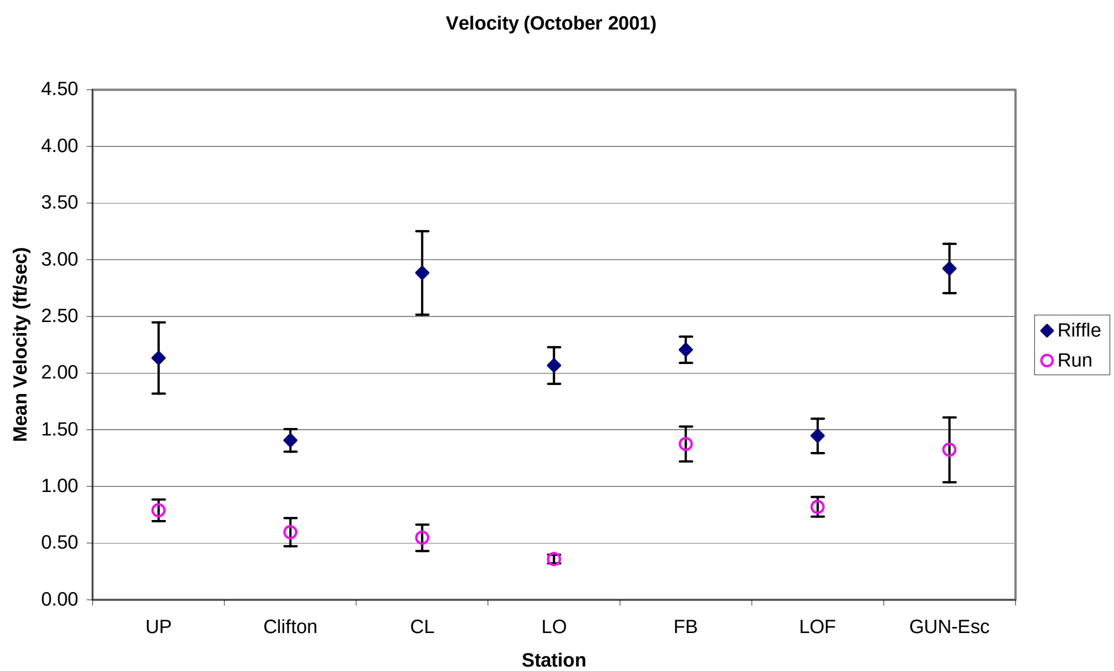


Figure 3-45. A comparison of mean current velocities (± 1 standard error) for samples taken at sites in the synoptic study area during August (top), and October (bottom), 2001.

3.2.2 Periphyton

3.2.2.1 Clifton Site

The total number of identifiable periphyton taxa increased through each year of the study. One hundred eleven periphyton taxa were identified during the 1999 sampling season, while 216 taxa had been identified by the 2003 season (see Volume 2 Appendix for detailed data). Metrics used to analyze periphyton data were summarized and compared between sites and among sampling seasons (Table 3-5). Biovolume was not measured during the first season of the study.

Periphyton data were highly variable between sampling occasions, site locations and even among repetitions. Values for most indices varied throughout each sampling season. Both habitats produced a wide range of values for most of the applied metrics. Density and taxa richness values provided few similarities in seasonal trends throughout the study period (Figures 3-46 and 3-47). Results of biovolume analysis provided some similarities in seasonal and spatial trends (Figure 3-48). In most cases riffle habitat accounted for greater biovolume than run habitat. These data suggest that periphyton communities can potentially increase in density and volume immediately following runoff, but often decrease to lower levels during the summer base flow months. Riffle habitat was capable of producing greater densities and volumes than run habitat.

Results of regression analysis identified several variables that were significant predictors of periphyton metrics (Table 3-6). The number of days below base turbidity (<50 NTU) prior to sampling had a significant positive impact on periphyton biovolume in riffle ($p = 0.0009$) and run ($p = 0.0575$) habitat. A significant ($p = 0.0134$) negative relationship was also found between biovolume in riffle habitat and Log (average daily discharge) prior to sampling. Taxa richness in riffle habitat was best described by a negative relationship with Log (average daily discharge). This suggests that periphyton communities sampled during the study period were primarily influenced by recent environmental conditions rather than peak flows.

Table 3-5. Monthly metrics and comparative values for periphyton samples collected from riffle and run habitat at the Clifton site in the "15 mile reach" of the Colorado River, Colorado.

	Diversity		Density (cells/mm^2)		Taxa Richness		Biovolume ($\mu m^3/mm^2$)	
	Riffle	Run	Riffle	Run	Riffle	Run	Riffle	Run
19 May 99	1.54	1.70	355,695	19,223	44	46		
9 Jun. 99	3.30	3.23	7,213	1,147	40	34		
13 Jul. 99	0.06	1.22	3,365,517	10,203	33	33		
19 Aug. 99	1.80	2.03	209,392	9,195	36	41		
16 Sep. 99	2.71	2.37	13,093	13,545	30	37		
27 Oct. 99	2.87	3.14	31,764	3,230	48	55		
	Riffle	Run	Riffle	Run	Riffle	Run	Riffle	Run
7 Jun. 00	0.23	1.07	364,713	394,270	24	31	2,264,698	2,181,145
12 Jul. 00	2.56	0.94	274,578	365,226	32	40	173,110,650	49,548,758
7 Aug. 00	1.50	1.69	736,656	369,024	55	49	22,295,965	10,041,306
16 Aug. 00	1.94	1.41	244,176	158,631	41	45	32,731,667	7,196,161
29 Aug. 00	1.70	0.34	202,308	354,504	46	39	17,741,801	10,851,271
12 Sep. 00	1.85	1.62	137,255	340,031	39	33	8,980,179	10,733,677
16 Oct. 00	4.09	1.49	70,242	171,255	48	40	88,553,276	39,835,192
	Riffle	Run	Riffle	Run	Riffle	Run	Riffle	Run
17 May 01	0.17	1.57	10,456	428	19	14	569,202	844,327
12 Jun. 01	2.08	1.17	74,302	22,782	31	28	12,037,112	2,405,669
12 Jul. 01	1.65	2.81	156,257	50,351	33	36	147,322,600	17,725,870
16 Aug. 01	2.39	2.73	19,371	15,526	20	23	69,596,141	50,801,117
28 Aug. 01	3.00	2.89	84,657	38,259	44	29	13,836,188	14,128,976
10 Sep. 01	3.65	2.88	26,785	29,103	39	36	15,526,544	17,381,675
18 Oct. 01	2.91	3.00	31,579	13,435	34	30	8,624,035	6,834,151
	Riffle	Run	Riffle	Run	Riffle	Run	Riffle	Run
27 Jun. 02	2.28	2.57	129,806	142,937	30	27	6,306,396,444	132,538,595
19 Jul. 02	3.62	3.17	189,885	32,484	47	33	932,275,958	35,146,647
16 Aug. 02	3.26	2.98	102,194	30,716	49	32	165,117,803	14,505,664
16 Sep. 02	2.67	2.35	81,071	89,847	29	32	9,108,734	9,288,389
16 Oct. 02	2.55	2.76	175,909	60,111	37	23	36,307,402	8,363,239
	Riffle	Run	Riffle	Run	Riffle	Run	Riffle	Run
16 Jul. 03	2.95	2.14	142,041	41,344	35	35	557,960,311	5,137,712
13 Aug. 03	2.73	3.15	153,585	15,177	30	32	1,100,112,087	5,360,958
3 Sep. 03	2.42	1.99	161,371	141,660	35	33	27,606,118	26,030,535
16 Sep. 03	2.67	2.55	167,976	22,258	34	25	44,775,656	4,716,584
21 Oct. 03	3.02	2.54	56,597	15,887	23	24	2,961,383,761	10,329,319

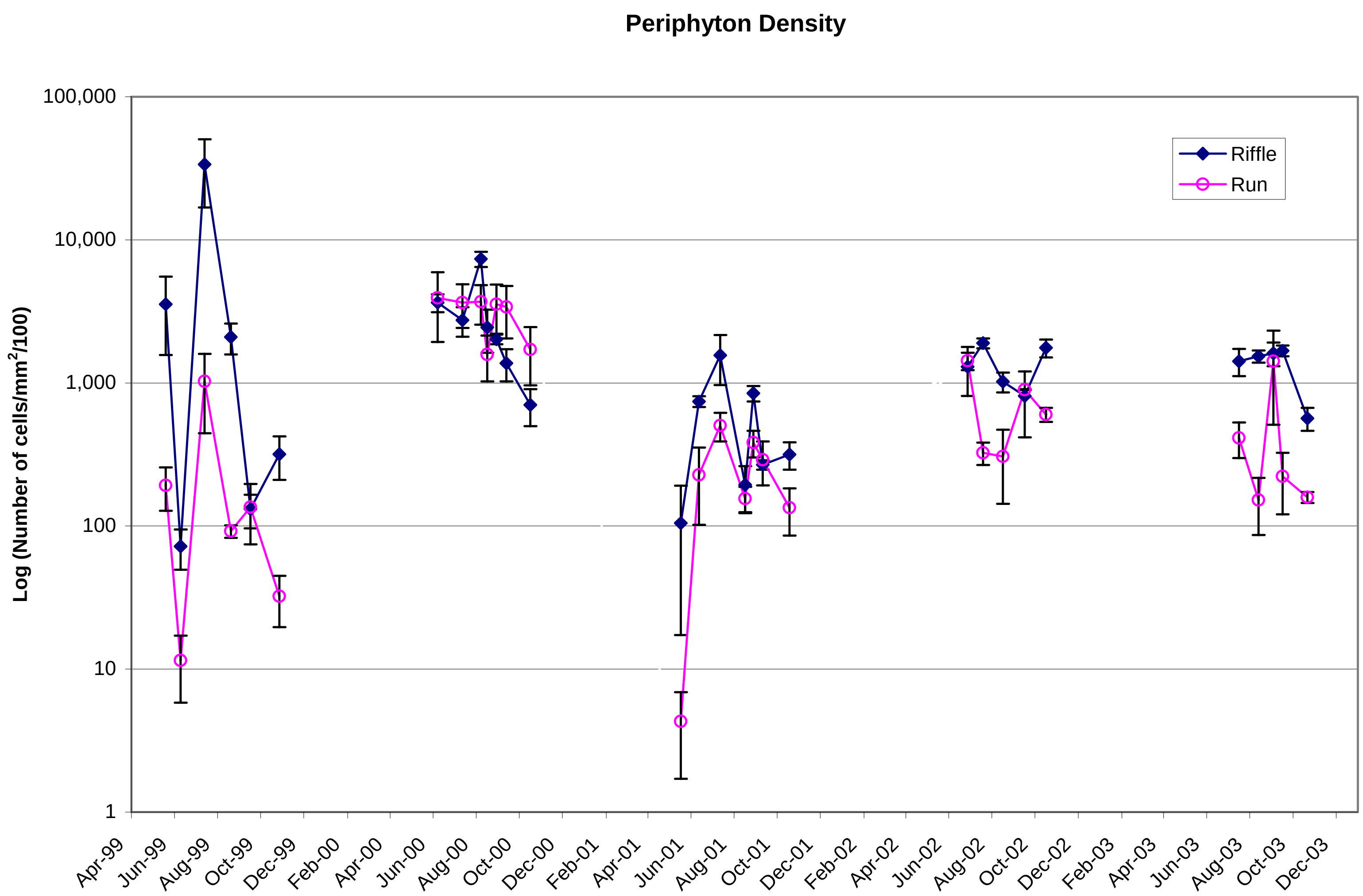


Figure 3-46. Density values (± 1 standard error) for periphyton collected from two habitats at the Clifton site in the 15-MR of the Colorado River, Colorado.

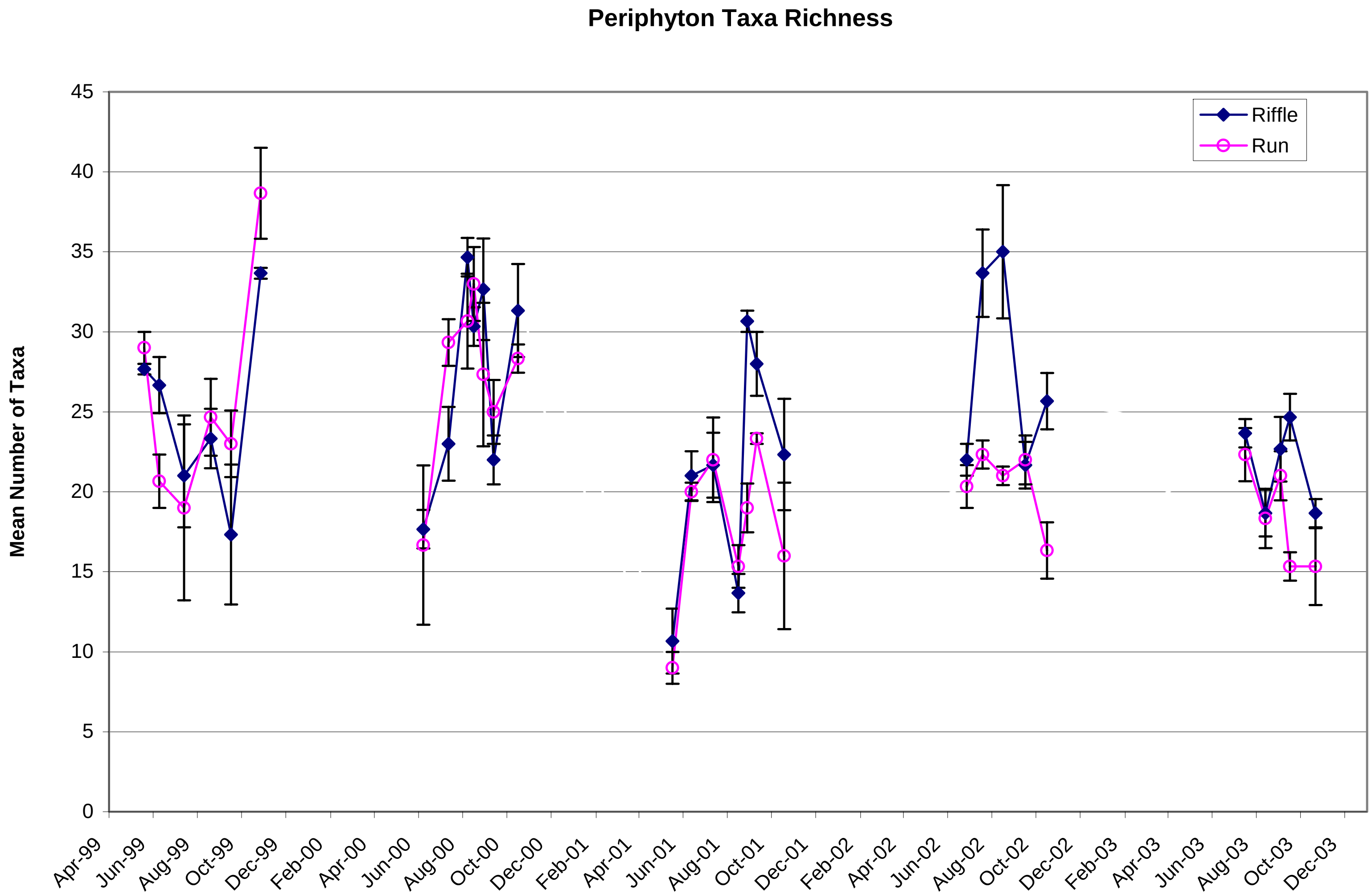


Figure 3-47. Taxa richness values (± 1 standard error) for periphyton collected from two habitats at the Clifton site in the 15-MR of the Colorado River, Colorado.

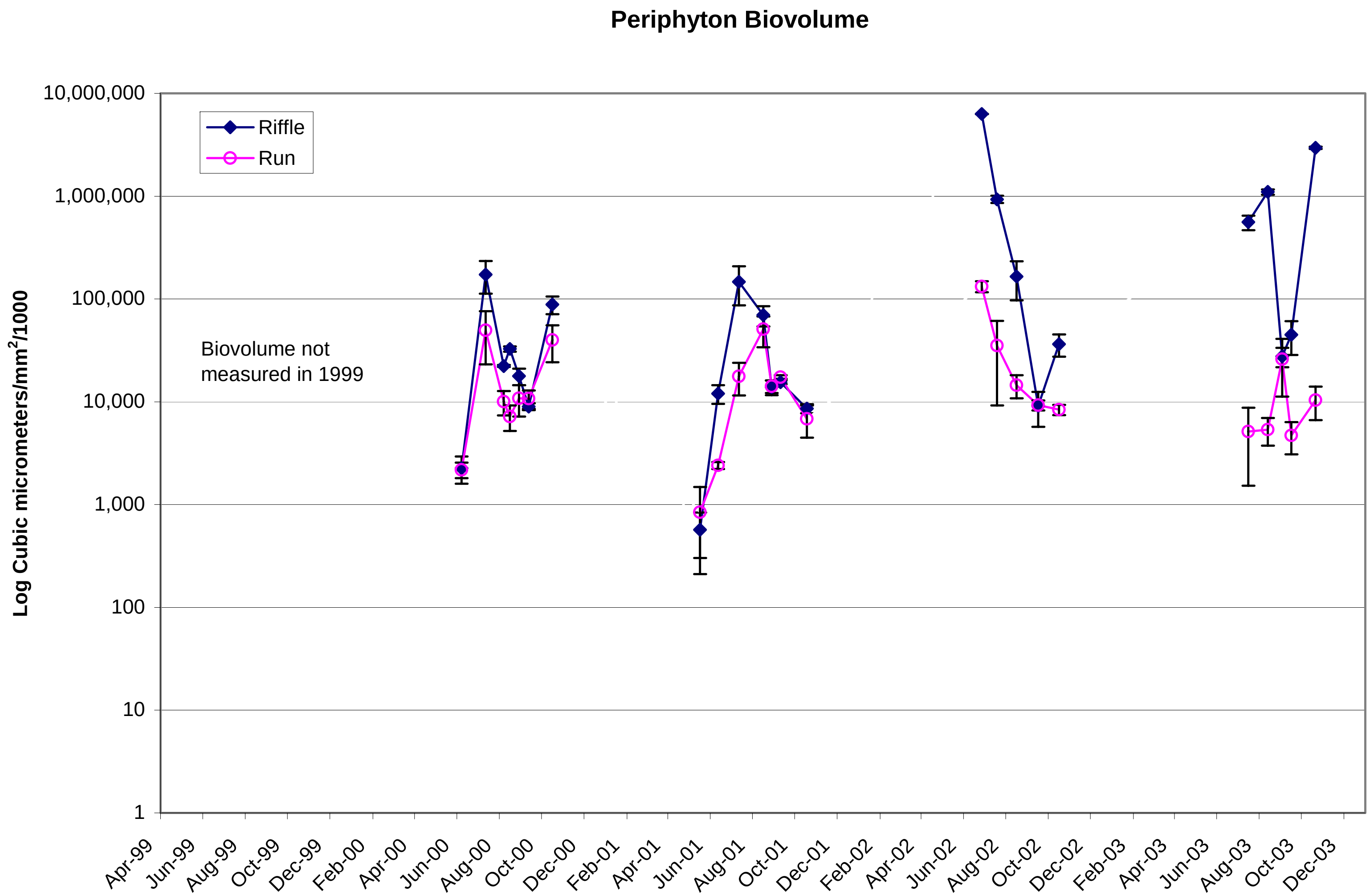


Figure 3-48. Mean biovolume (± 1 standard error) of periphyton collected from two habitats at the Clifton site in the 15-MR of the Colorado River, Colorado.

Table 3-6. Periphyton regression table.

Richness	Riffle				Run			
	Mean	SE	t Value	Pr > |t|	Mean	SE	t Value	Pr > |t|
OVERALL MODEL SIGNIFICANCE	F=3.83, P=0.0342, Adj-R2=0.1635				F=3.15, P=0.0589, Adj-R2=0.1292			
Intercept	6.8490	0.7696	8.90	**<0.0001**	4.3197	0.2255	19.16	**<0.0001**
Percent change in turbidity	-0.2133	0.1159	-1.84	0.0766	-0.1610	0.1169	-1.38	0.1796
Log (average daily discharge)	-0.2710	0.1062	-2.55	**0.0167**	na	na	na	na
No. days below base turbidity (<50 NTU)	na	na	na	na	0.5911	0.3467	1.71	0.0997
Density	**Riffle**				**Run**			
	Mean	SE	t Value	Pr > |t|	Mean	SE	t Value	Pr > |t|
OVERALL MODEL SIGNIFICANCE	F=3.48, P=0.0725, Adj-R2=0.0789				F=2.66, P=0.1143, Adj.-R2=0.0541			
Intercept	1.6837	0.1859	9.06	**<0.0001**	1.2535	0.2195	5.71	**<0.0001**
No. days below base turbidity (<50 NTU)	0.5315	0.2848	1.87	0.0725	0.5483	0.3363	1.63	0.1143
Biovolume	**Riffle**				**Run**			
	Mean	SE	t Value	Pr > |t|	Mean	SE	t Value	Pr > |t|
OVERALL MODEL SIGNIFICANCE	F=8.89, P=0.0016, Adj-R2=0.4069				F=2.95, P=0.0407, Adj.-R2=0.2976			
Intercept	6.4582	1.0244	6.30	**<0.0001**	3.2685	1.1258	2.90	**0.0095**
No. days below base turbidity (<50 NTU)	1.8659	0.4819	3.87	**0.0009**	0.8034	0.3960	2.03	**0.0575**
Log (average daily discharge)	-0.4126	0.1527	-2.70	**0.0134**	0.0734	0.1918	0.38	0.7064
Annual Peakflow	na	na	na	na	0.0001	0.0001	1.03	0.3184
Annual peakflow* log(avg. daily discharge)	na	na	na	na	0.0000	0.0000	-1.22	0.2364
Log (# days above threshold of 400 NTU)	na	na	na	na	0.1953	0.1575	1.24	0.2311

3.2.2.2 Synoptic Study Sites

During the 2001 sampling season several sites were added to the monitoring program in order to collect representative data from other reaches of the Colorado River drainage, and determine if observations from the Clifton site would be representative of these other areas. The results of this sampling are presented in Volume II, Appendix A. Metrics used to analyze periphyton data were summarized and compared between sites (Table 3-7). Only riffle habitat was sampled in May.

Table 3-7. Metrics and comparative values for periphyton samples collected from riffle and run habitat in the expanded study area of the Colorado and Gunnison rivers, Colorado.

17 May 01	**Diversity**		**Density (cells/mm^2)**		**Species Richness**		**Biovolume ($\mu m^3/mm^2$)**	
Site	Riffle	Run	Riffle	Run	Riffle	Run	Riffle	Run
UP	1.14		401		17		112,921	
Clifton	0.17		10,456		19		569,202	
LO	1.47		277		15		83,204	
FB	2.84		98		12		226,849	
LOF	2.91		61		13		115,816	
28 Aug. 01	**Diversity**		**Density (cells/mm^2)**		**Species Richness**		**Biovolume ($\mu m^3/mm^2$)**	
Site	Riffle	Run	Riffle	Run	Riffle	Run	Riffle	Run
UP	2.57	2.83	77,987	15,202	37	31	5,218,557	26,258,545
Clifton	3.00	2.89	84,657	38,259	44	29	13,836,188	14,128,976
CL	2.71	3.11	56,619	21,828	46	39	40,392,023	68,753,939
LO	2.00	2.73	144,362	21,199	39	27	21,722,058	3,200,940
FB	2.22	1.83	122,028	33,322	32	25	46,957,969	11,260,489
LOF	2.64	1.90	36,923	25,552	28	27	47,518,758	25,401,003
GUN-Esc	2.26	2.66	57,053	23,344	37	31	31,025,186	3,701,135
18 Oct. 01	**Diversity**		**Density (cells/mm^2)**		**Species Richness**		**Biovolume ($\mu m^3/mm^2$)**	
Site	Riffle	Run	Riffle	Run	Riffle	Run	Riffle	Run
UP	2.28	2.54	55,884	12,281	21	24	49,105,804	6,969,924
Clifton	2.91	3.00	31,579	13,435	34	30	8,624,035	6,834,152
CL	2.45	2.47	73,432	45,479	31	33	30,942,816	20,491,916
LO	3.06	2.74	61,882	3,087	47	23	11,371,817	13,022,867
FB	3.17	2.20	54,936	55,157	36	29	20,055,283	21,648,206
LOF	1.54	0.80	130,197	196,928	33	30	14,315,999	11,767,964
GUN-Esc	2.94	2.86	56,986	25,795	33	28	60,487,957	48,927,812

Metric values from the expanded site locations indicated that periphyton communities varied among locations and seasons. Density values peaked in run habitat during October at site LOF, but were usually higher in riffle habitat during most sampling occasions (Figure 3-49). Density values from run habitat during the August sampling occasion were most consistent of the density related comparisons among sites. Species richness exhibited less variation among sites than other metrics, and was consistently lowest at all sites during May (Figure 3-50). Species richness was also higher in riffle habitat at all sites in August and all but two locations in October. Biovolume was similar to density in that results were variable among sites, and values were consistently lower at all sites during May (Figure 3-51). However, biovolume did not appear to be correlated to density or any other metrics.

3.2.2.3 Macroinvertebrates (Clifton Site)

Data from macroinvertebrate sampling was evaluated using the previously described metrics. The data from macroinvertebrate sampling are presented in Volume II, Appendix B. The metrics applied in this study emphasize different types of information. This information includes, but is not limited to: 1) water quality related changes in community structure, 2) changes in communities related to habitat preference, 3) habitat related changes in standing crop, and 4) changes in macroinvertebrate community function. This information can be used to determine the cause of changes in biological communities imposed by physical attributes at each site, and to determine the influences of different physical processes on biological communities between years.

Metrics used to analyze macroinvertebrate data were summarized and compared between habitats throughout the sampling period (Table 3-8). Diversity, evenness and the F.B.I. are primarily water quality metrics that are sensitive to different types of organic pollution. These metrics should be similar between habitats because pollution induced changes are not anticipated in the study area. Metrics that are more sensitive to habitat preference include species richness and the E.P.T. index. Values produced by these metrics report the total number of species, and number of "sensitive" species found in each habitat. Metrics designed to measure standing crop include density and biomass. These indices are valuable when comparing production between habitat types. Finally, the analysis of functional feeding groups was used to detect changes in community function based on feeding strategy.

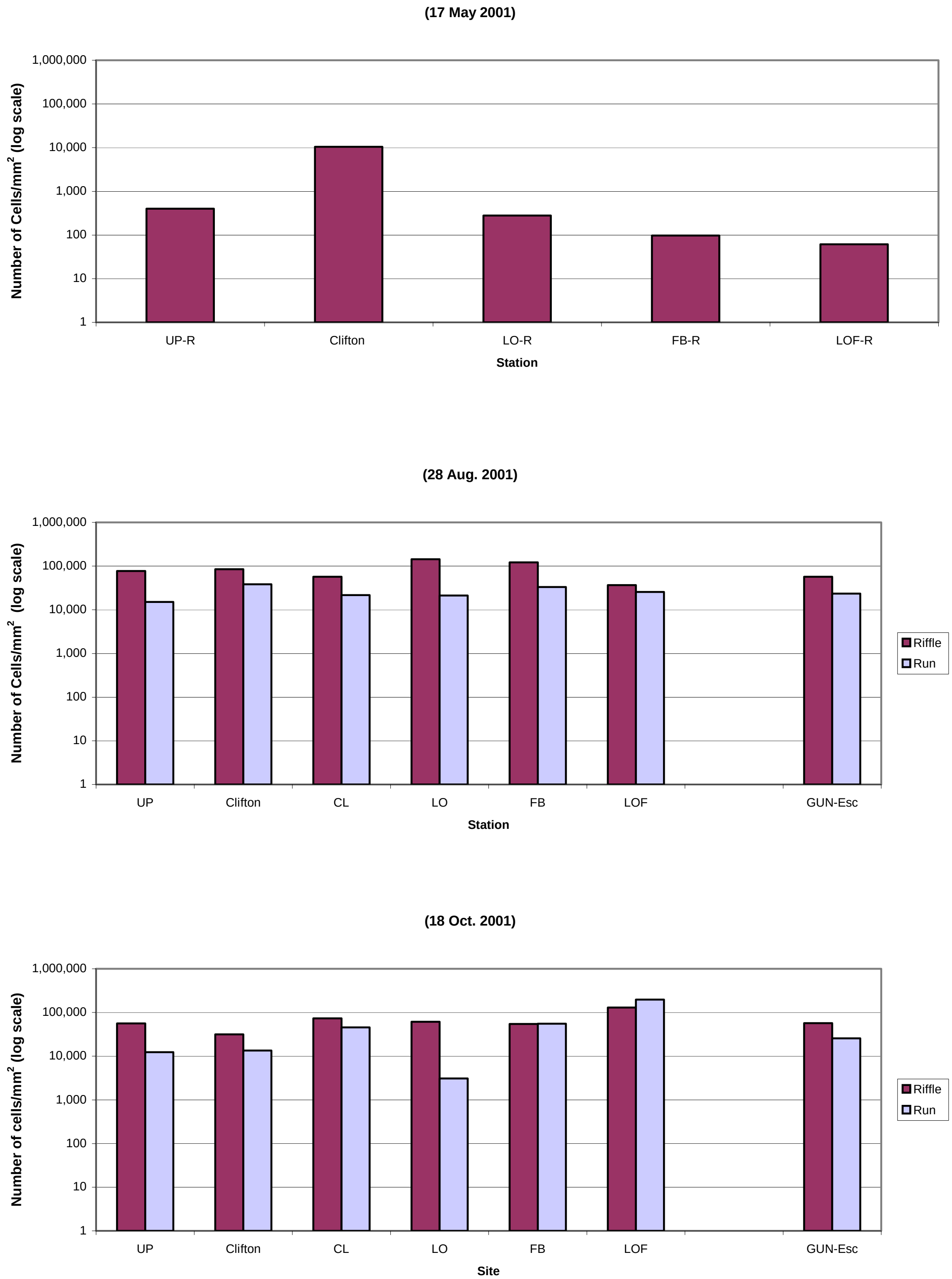


Figure 3-49. Density values for periphyton collected in May (top), August (middle), and October (bottom), 2001 from the Colorado and Gunnison rivers, Colorado.

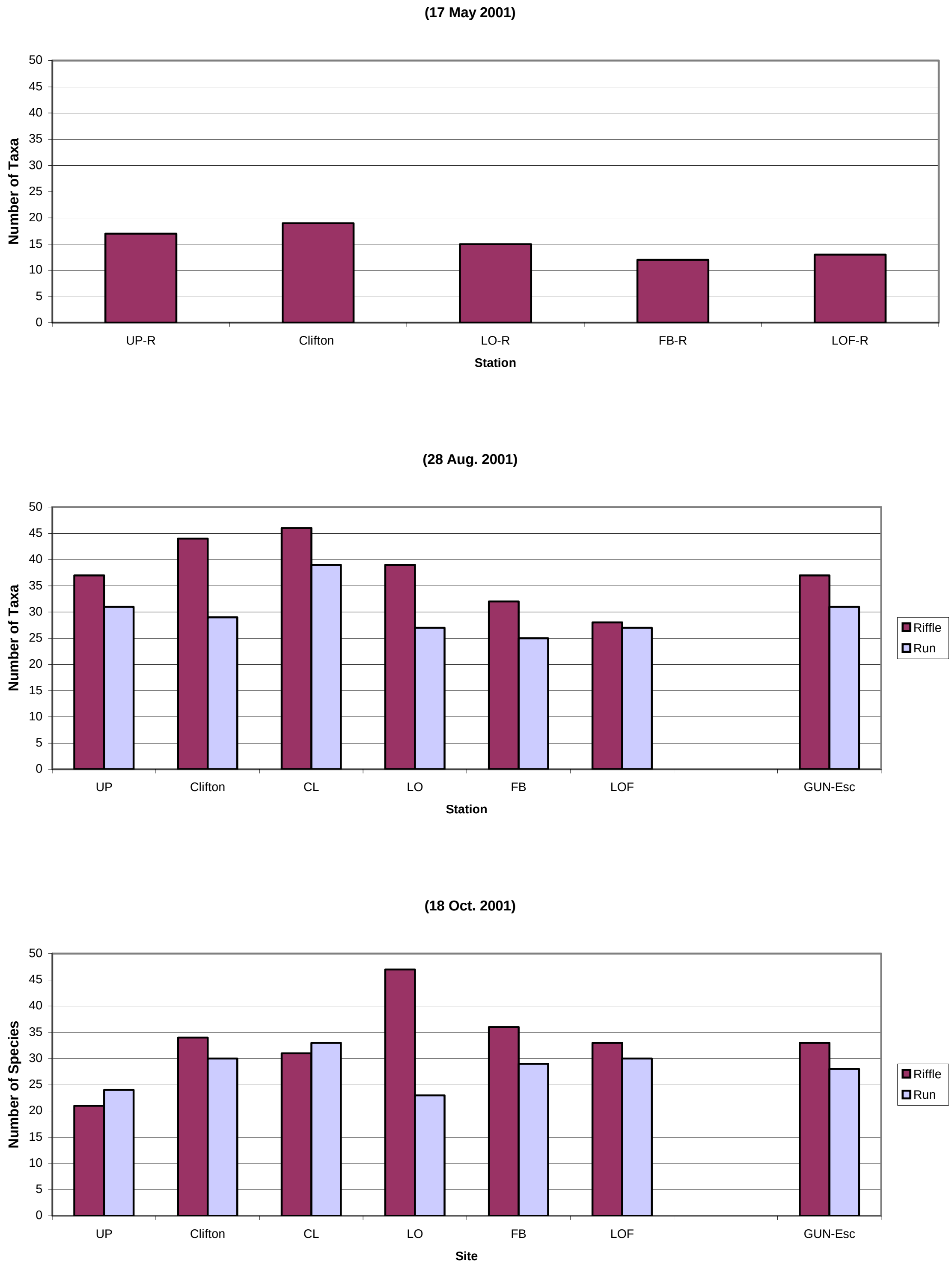


Figure 3-50. Species richness values for periphyton collected in May (top), August (middle), and October (bottom), 2001 from the Colorado and Gunnison rivers, Colorado.

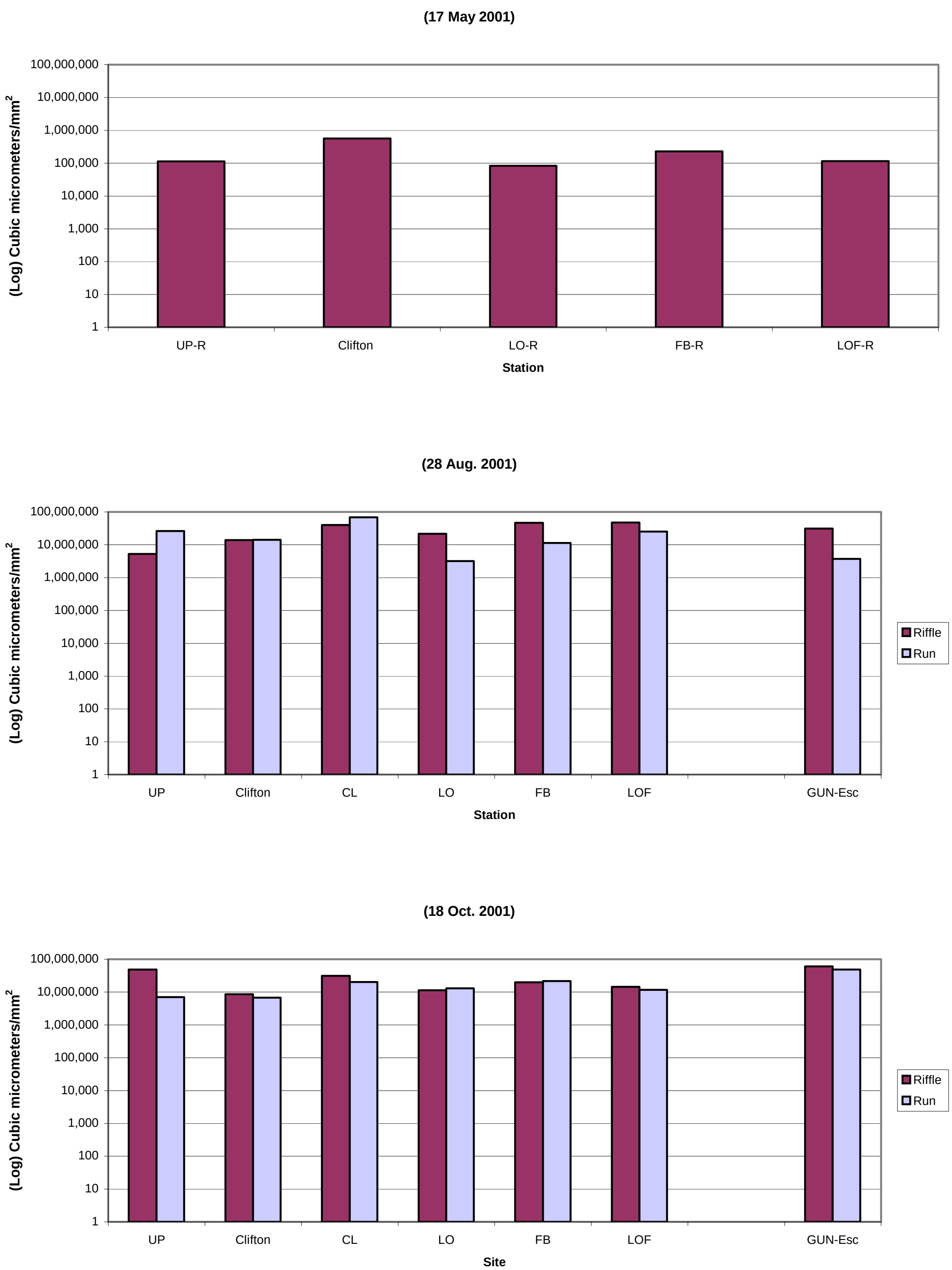


Figure 3-51. Biovolume values for periphyton collected in May (top), August (middle), and October (bottom), 2001 from the Colorado and Gunnison rivers, Colorado.

Table 3-8. Monthly metrics and comparative values for macroinvertebrate samples collected from riffle and run habitat in the "15 mile reach" of the Colorado River, Colorado.

	Diversity		Evenness		FBI		EPT		Taxa Richness		Density (#/m²)		Biomass (g/m²)	
	Riffle	Run	Riffle	Run	Riffle	Run	Riffle	Run	Riffle	Run	Riffle	Run	Riffle	Run
19 May 99	2.61	1.77	0.604	0.631	5.70	6.67	8	3	20	7	3,468	314	1.7434	0.2070
9 June 99	2.64	2.46	0.675	0.628	4.17	4.20	7	8	15	15	706	564	0.3038	0.3268
13 July 99	3.55	2.64	0.709	0.602	4.94	5.14	20	11	32	21	5,838	3,088	0.6582	0.2348
19 Aug. 99	3.19	3.15	0.638	0.707	4.10	4.42	22	14	32	22	9,682	2,045	1.6881	0.3349
16 Sept. 99	3.14	3.48	0.616	0.818	4.62	5.42	22	12	35	19	23,119	951	3.0035	0.3026
27 Oct. 99	3.01	2.96	0.614	0.724	5.76	5.99	16	10	30	17	18,941	1,461	3.4258	0.4684
	Diversity		**Evenness**		**FBI**		**EPT**		**Taxa Richness**		**Density (#/m²)**		**Biomass (g/m²)**	
17 May 00	2.60	2.05	0.649	0.593	6.95	7.80	9	6	16	11	1,749	759	0.8470	0.2186
7 June 00	3.38	3.43	0.757	0.840	4.25	4.77	12	11	22	17	2,497	633	1.0046	0.5581
12 July 00	3.54	3.06	0.675	0.659	4.72	5.10	25	19	38	25	35,056	5,324	4.0702	0.9079
7 Aug. 00	3.16	3.03	0.603	0.679	4.38	5.42	22	12	38	22	31,826	3,180	8.0138	0.7330
16 Aug. 00	3.30	3.41	0.673	0.753	4.84	5.52	18	13	30	23	20,449	2,708	5.8274	1.0253
29 Aug. 00	3.52	2.77	0.717	0.708	5.31	6.08	17	5	30	15	6,256	1,400	1.5719	0.1243
12 Sept. 00	3.26	3.18	0.647	0.736	4.69	5.77	18	11	33	20	9,969	1,385	2.6789	0.2463
16 Oct. 00	2.84	2.70	0.573	0.624	4.58	6.20	17	10	31	20	21,346	2,842	6.4327	0.3694
	Diversity		**Evenness**		**FBI**		**EPT**		**Taxa Richness**		**Density (#/m²)**		**Biomass (g/m²)**	
17 May 01	2.48	2.87	0.606	0.775	5.68	5.47	8	6	17	13	1,730	368	0.2946	0.2969
12 June 01	1.56	0.91	0.334	0.205	5.87	5.97	13	9	23	15	6,176	2,401	1.6985	0.1623
12 July 01	3.82	3.26	0.750	0.702	5.18	5.85	20	15	34	25	13,425	3,092	2.7342	0.5339
16 Aug. 01	3.50	2.17	0.721	0.586	6.21	7.93	15	4	29	13	4,630	882	0.7514	0.1070
28 Aug. 01	3.92	2.90	0.784	0.709	4.98	6.72	17	7	32	17	5,715	1,270	0.8504	0.1024
10 Sept. 01	3.09	2.98	0.637	0.745	4.81	6.09	14	7	29	16	14,822	2,957	1.4292	0.2428
18 Oct. 01	2.71	2.63	0.542	0.657	5.13	6.31	15	6	32	16	18,366	4,231	3.9954	0.6916
	Diversity		**Evenness**		**FBI**		**EPT**		**Taxa Richness**		**Density (#/m²)**		**Biomass (g/m²)**	
27 June 02	2.64	2.31	0.519	0.511	4.86	7.71	21	12	34	23	64,262	9,194	4.8953	0.5144
19 July 02	2.66	2.76	0.532	0.609	4.48	5.87	19	8	32	23	55,416	3,322	8.2290	0.4315
16 Aug. 02	2.58	2.94	0.543	0.704	4.24	6.10	13	5	27	18	19,363	2,056	6.5224	0.2152
16 Sept. 02	2.51	2.79	0.522	0.698	4.20	6.67	14	6	27	16	22,148	1,197	4.2693	0.1082
16 Oct. 02	2.37	2.63	0.487	0.672	4.35	6.42	14	4	29	15	18,845	798	4.7296	0.0690
	Diversity		**Evenness**		**FBI**		**EPT**		**Taxa Richness**		**Density (#/m²)**		**Biomass (g/m²)**	
16 July 03	3.59	2.96	0.705	0.630	4.68	4.84	22	16	34	26	11,703	2,865	1.1036	0.2762
13 Aug. 03	3.07	3.17	0.609	0.759	5.04	5.39	20	11	33	18	15,240	2,198	2.2520	0.4983
3 Sept. 03	3.41	2.43	0.664	0.517	4.73	5.83	20	11	35	26	7,277	3,905	1.3867	0.3349
16 Sept. 03	3.59	3.32	0.747	0.781	4.32	5.95	16	8	28	19	8,178	430	1.7687	0.0265
21 Oct. 03	2.86	2.25	0.601	0.512	5.11	7.74	13	9	27	21	15,854	3,817	2.2992	0.2175

3.2.2.3.1 Water Quality Metrics

Diversity, Evenness and F.B.I. values were compared for each habitat on each sampling date during the study period (Figures 3-52, also see Appendix B, Figures 25 and 26). Values suggest that each site exhibited a representative macroinvertebrate community for a larger Colorado Plateau river. Although these metrics were designed to indicate different types of disturbance, they are primarily indicators of pollution and are less sensitive to natural changes in habitat. Results obtained from each metric provides insight into variations of the data.

Diversity and evenness values exhibited some fluctuation between habitats and sampling events, but generally remained within a range that is considered to be indicative of good water quality at both (riffle and run) locations (Table 3-8). Low values for these metrics often occurred in the spring or early summer suggesting that these metrics may be reflecting adverse conditions occurring with runoff. This trend among seasons was particularly true for diversity values. Lowest diversity values from both habitats were recorded in May or June each year. Evenness values remained fairly consistent throughout the sampling seasons, but exhibited a sharp decline in June of 2001. Lowest diversity and evenness values were produced during June 2001. As expected, results of both metrics indicated there was little difference in water quality between sampling sites throughout the study period.

The FBI is similar to the two previously described indices because it is usually used to detect organic pollution, and may be influenced to a small degree by the natural variation of habitats in the same reach of a stream. The FBI works by rating families of macroinvertebrates according to a predetermined tolerance of organic pollution (Hilsenhoff 1988). Part of the criteria for assigning a tolerance value to invertebrate taxa is based on the oxygen requirements of that species. Species that require high concentrations of oxygen are usually adapted to live in habitats that meet these requirements (i.e. riffles). Although water quality was probably similar at each habitat location, a slight bias was likely when comparing FBI data between habitats (Table 3-8). The habitat type with less current velocity (run) was colonized by a greater proportion of macroinvertebrates with lower oxygen requirements, and those results were reflected in the FBI values. FBI values exhibited little variation throughout the sampling seasons.

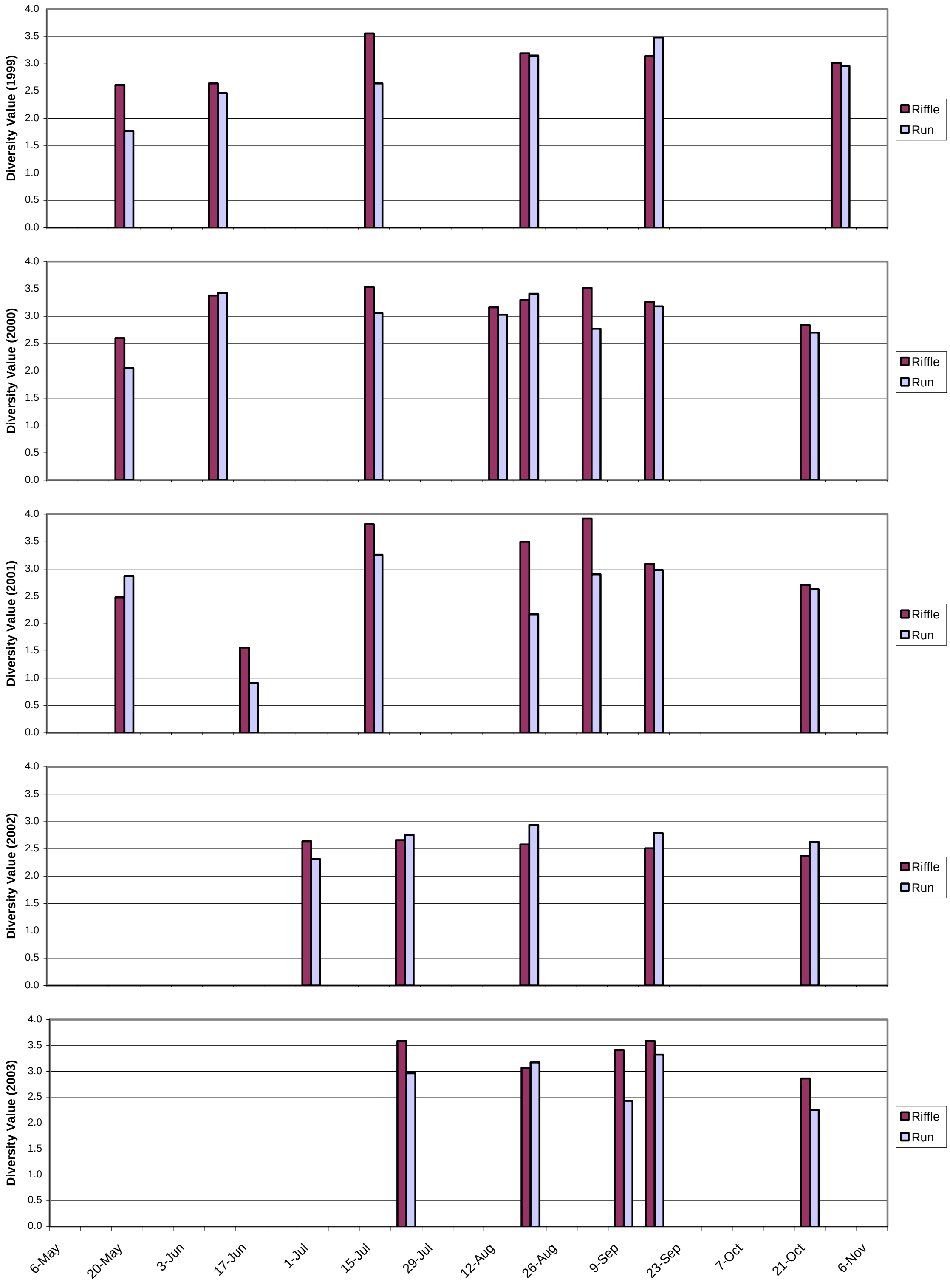


Figure 3-52. Diversity values for macroinvertebrates collected from two habitats from 1999 (top), through 2003 (bottom), at the Clifton site in the 15-MR of the Colorado River, Colorado.

3.2.2.3.2 Richness Metrics

Taxa richness and EPT index were used to measure numbers of taxa present at each location. EPT includes only taxa from Orders that are considered to be more sensitive to disturbances, and species richness includes all taxa. EPT values were obtained by pooling data from the replicates at each site. Taxa richness values were obtained for each replicate to generate mean values for each sampling event. Results obtained by these metrics indicated consistent differences between the habitats (Figures 3-53 and 3-54).

A comparison between taxa richness and EPT values indicated similar trends between habitats throughout the sampling seasons; however, the observed trends were not as similar among years (Figures 3-53 and 3-54). During all sampling occasions (except June 1999) the values for both metrics were higher in the riffle habitat than run habitat. The results suggest that values produced by these metrics were highest during periods of relatively stable flow following snowmelt runoff. The highest values for both metrics during the study period were observed during July 2000 at a time of relatively low stable flow. Most of the low values occurred during the period of high flows associated with snowmelt runoff; however occasional declines in these metric values were observed during the mid-summer months particularly in run habitat. Variations that occurred during mid to late summer months were not consistent among years. Results produced by both metrics suggested that the specific habitat provided by riffles was preferred by more species than the habitat provided in runs. The number of different taxa increased (or became more concentrated) in both habitats during periods of lower and/or stable flow that immediately follows the peak flow (see Figure 3-17 for discharge and Figure 3-54 for richness).

3.2.2.3.3 Production Metrics

Density and biomass were used as a measurement of standing crop and an indication of macroinvertebrate production throughout the study period. Although these measurements are often related they do not always indicate the same trends. Density is a count based on the total number of individuals, whereas biomass is a function of the number and relative weight of individuals. Results provided by these metrics indicated that production was almost always greatest in riffle habitat (Figures 3-55 and 3-56). The only exceptions to this trend were the biomass values reported during the periods of high flow associated with runoff. During all sampling seasons these metrics indicated

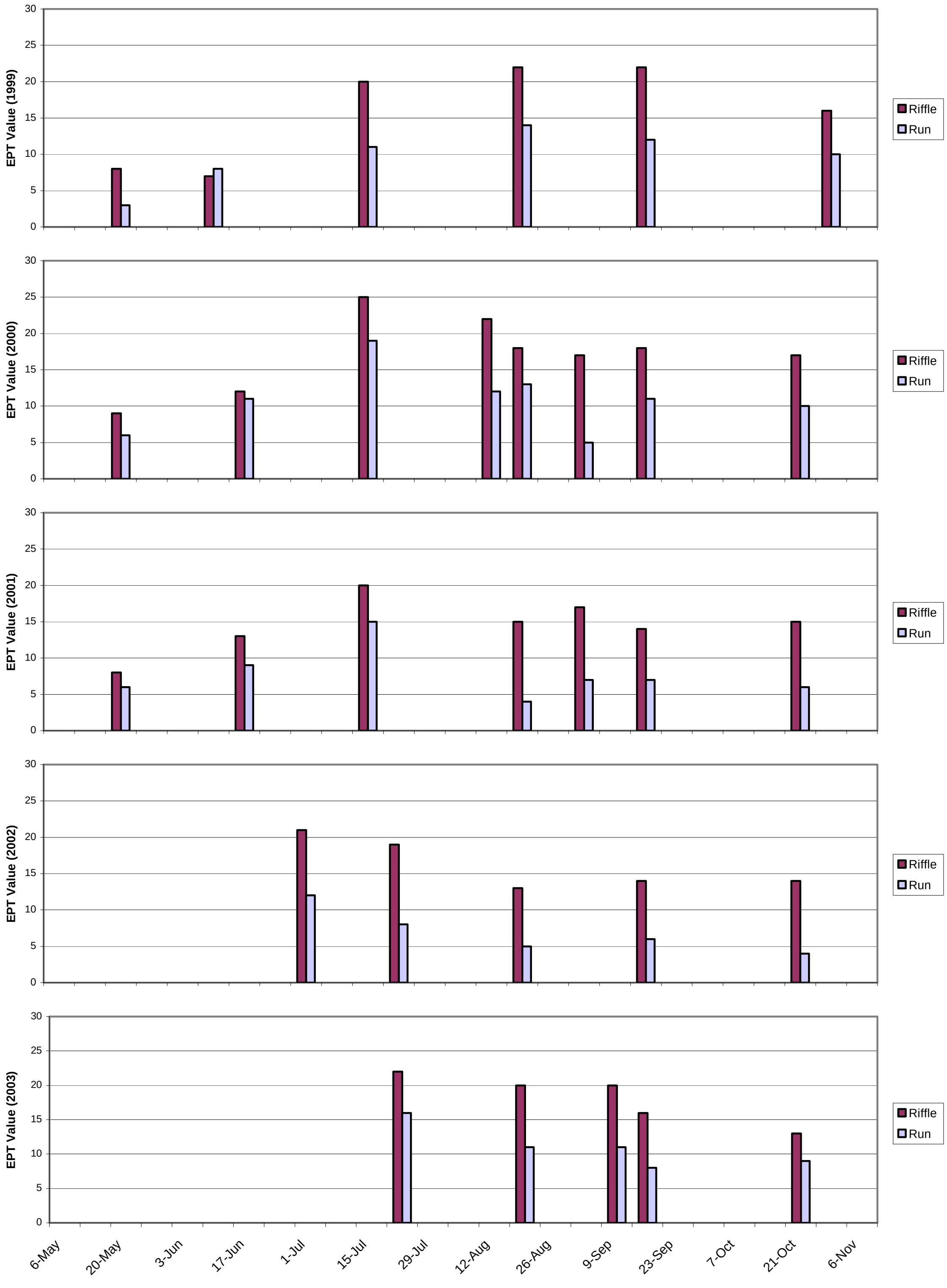


Figure 3-53. EPT values for macroinvertebrates collected from two habitats from 1999 (top), through 2003 (bottom), at the Clifton site in the 15-MR of the Colorado River, Colorado.

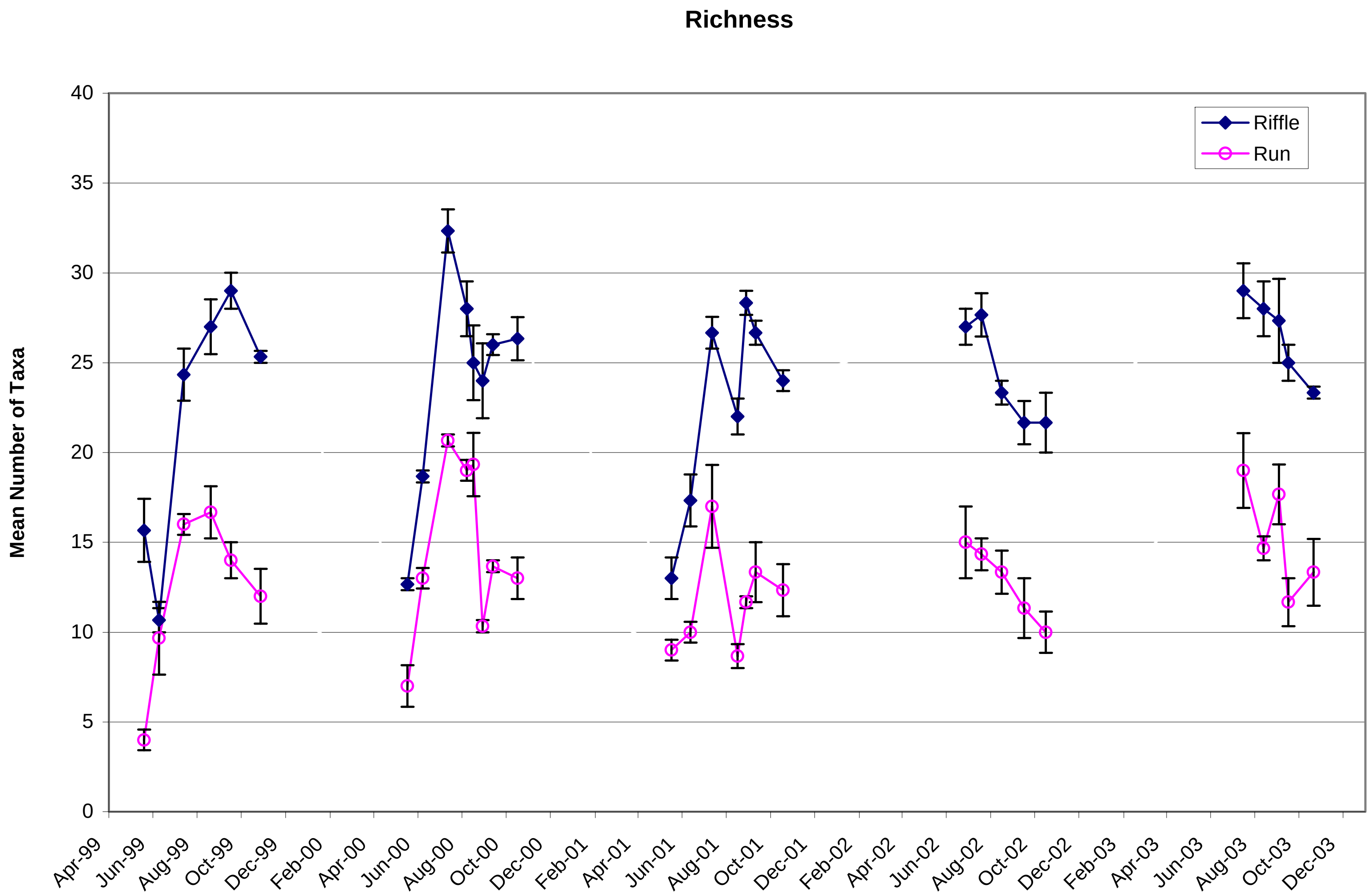


Figure 3-54. Mean taxa richness values (± 1 standard error) of macroinvertebrates collected from two habitats at the Clifton site in the 15-MR of the Colorado River, Colorado.

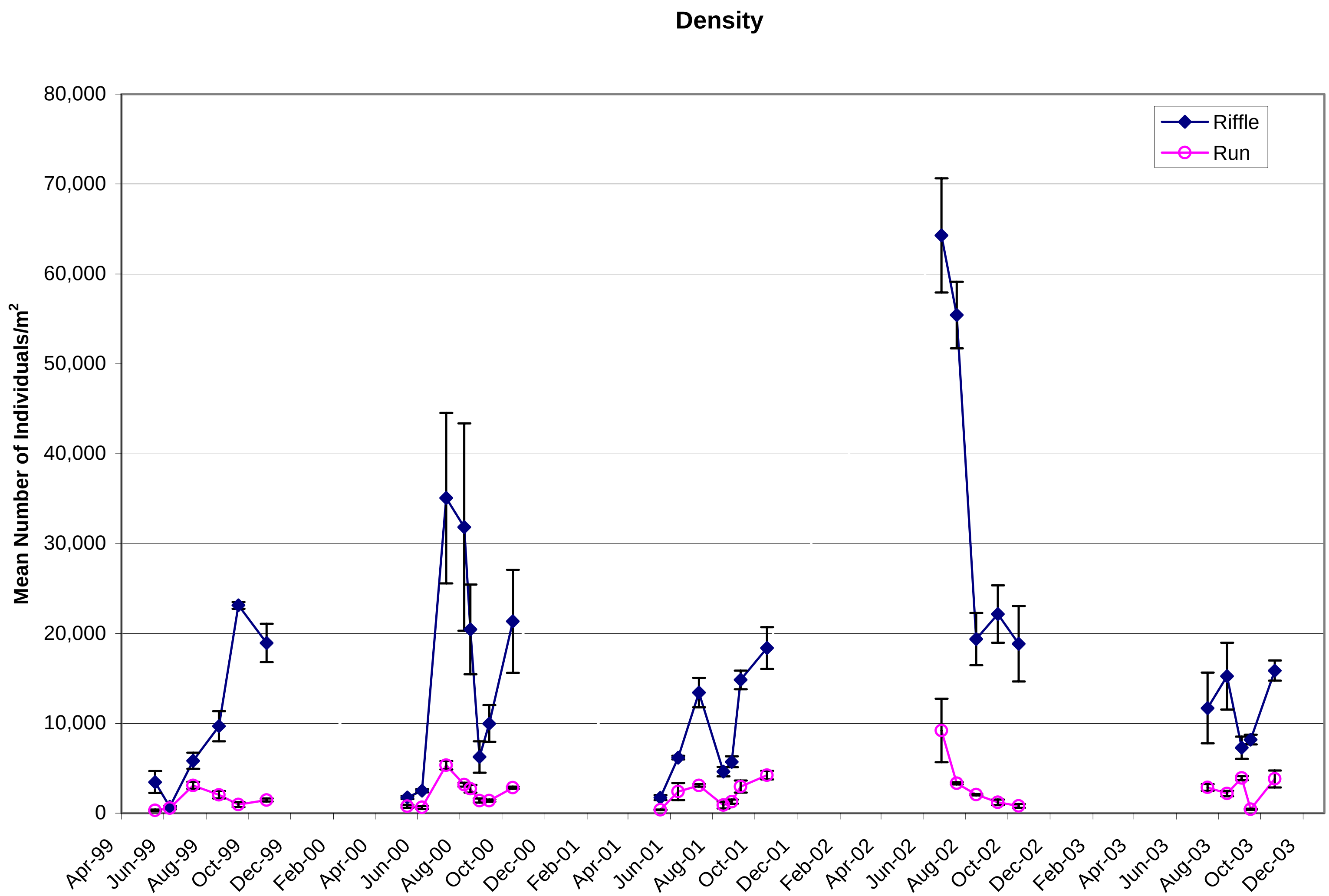


Figure 3-55. Mean density (± 1 standard error) of macroinvertebrates collected from two habitat types at the Clifton site in the 15-MR of the Colorado River, Colorado.

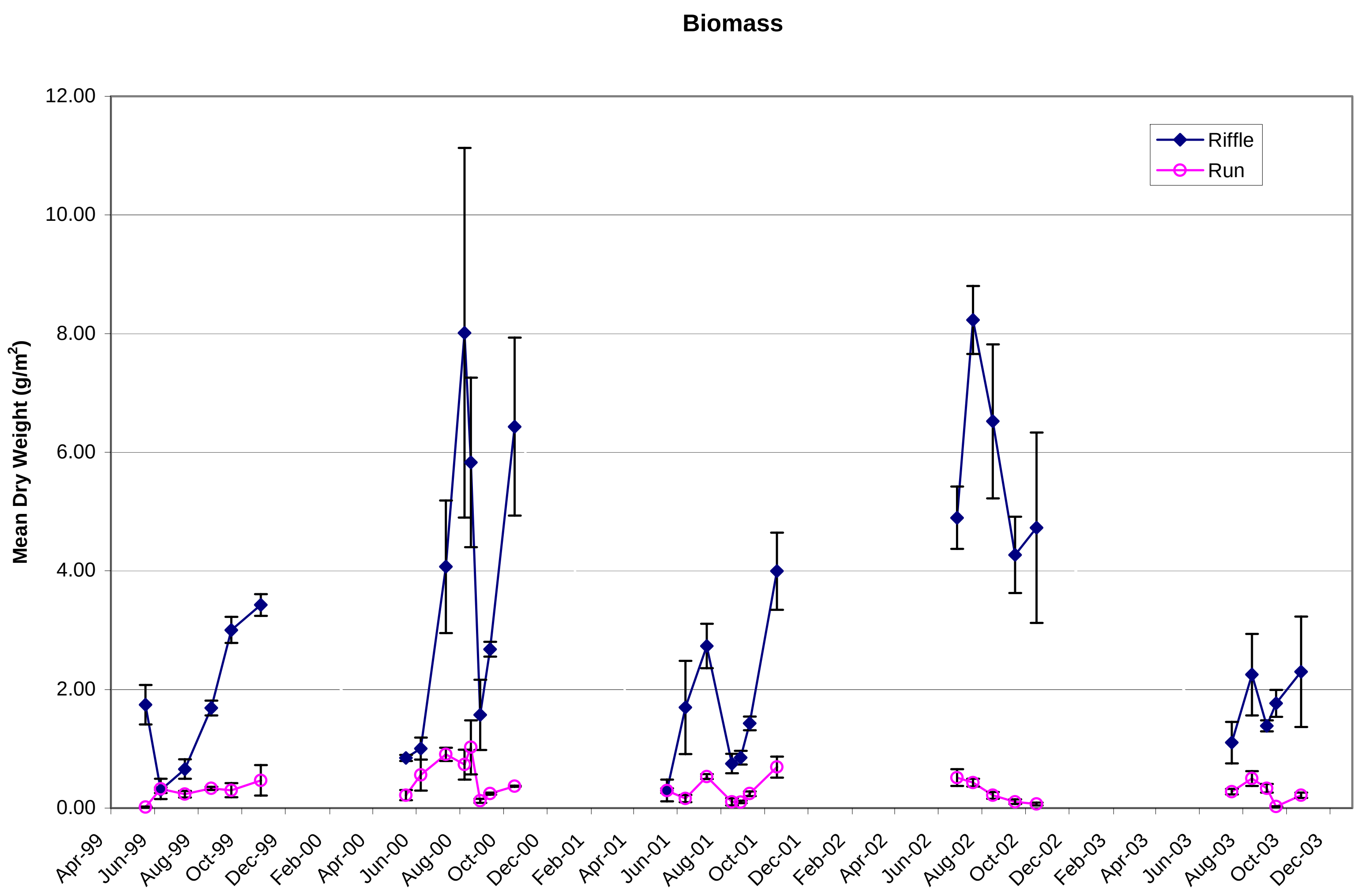


Figure 3-56. Mean biomass (± 1 standard error) of macroinvertebrates collected from two habitats at the Clifton site in the 15-MR of the Colorado River, Colorado.

a substantial increase in standing crop in riffle habitat during the post-runoff summer months, however, the trends displayed throughout each season were not always similar when compared among years. During 1999 peak density and biomass values occurred in September and October, respectively. Analysis of data collected in 2000 indicated that peak density occurred in July and peak biomass occurred during August. In 2001 these metric values were highest in October, but also exhibited relatively high values in July. Peaks occurred during July and October during the following years. Peak values for these production-related metrics were much greater in 2000 and 2002 than they were in other years. This lack of seasonal associations in metric values has been observed in several biological metrics used during this study and suggests the seasonal influence may not be the dominant force controlling these communities.

Density of invertebrates in riffles ranged from 1.3 to 24.3 times higher than density in run habitat. On average the density of invertebrates in riffles was 6.9 times higher than the density in run habitat. Biomass values show a similar relationship. Biomass of invertebrates in riffles ranged from 0.9 to 85.8 times the biomass in run habitat. On average the biomass of invertebrates in riffles was 8.5 times the biomass in run habitat. This demonstrates that a much greater proportion of the standing crop exists in the faster velocity areas of the river.

Results of regression analysis identified variables that were significant predictors of macroinvertebrate richness, density, and biomass in riffle and run habitat (Table 3-9). The number of days with turbidity values less than 50 NTU's prior to sampling had a significant positive influence on all biological responses. This variable was the only significant variable in the models for richness and biomass in run habitat. The only other variable that was significant in the model for density in run habitat was average daily discharge. Average daily discharge had a significant negative relationship with density in run habitat, and in each of the models for biological responses in riffle habitat. An increase in the percent change in turbidity was also found to have a negative impact on macroinvertebrate density in riffle habitat (Table 3-9). Annual peak flow was not a significant variable in any of the regression models.

Table 3-9. Macroinvertebrate regression table.

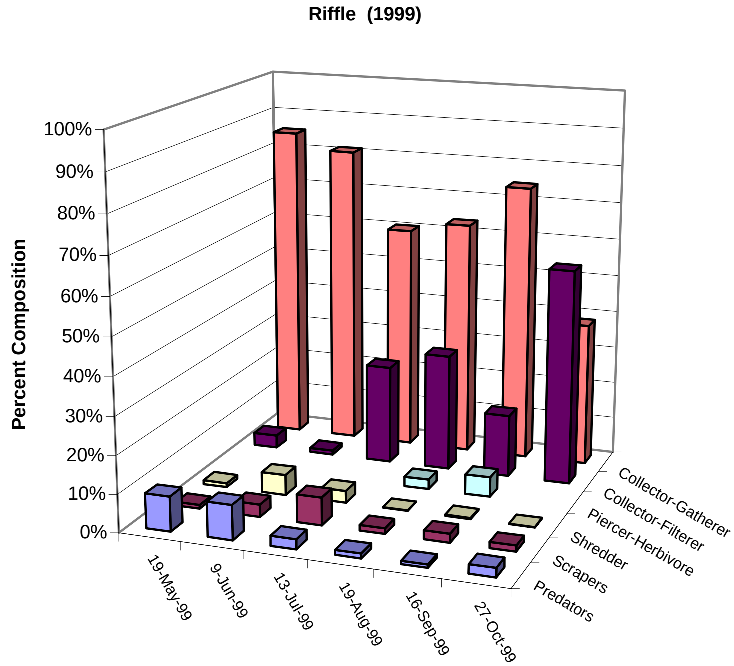
Richness	Riffle				Run			
	Mean	SE	t Value	Pr > |t|	Mean	SE	t Value	Pr > |t|
OVERALL MODEL SIGNIFICANCE	F=24.77, P=0.0001, Adj-R2=0.7038				F=12.55, P=0.0001, Adj-R2=0.4350			
Intercept	4.8529	0.4551	10.66	**<0.0001**	2.7836	0.2120	13.13	**<0.0001**
No. days below base turbidity (<50 NTU)	1.4416	0.1936	7.45	**<0.0001**	1.2341	0.2516	4.91	**<0.0001**
Log (average daily discharge)	-0.1592	0.0545	-2.92	**0.0070**	na	na	na	na
Log (# days above turbidity threshold of 400 NTU)	0.3791	0.0821	4.62	**<0.0001**	0.1423	0.1018	1.40	0.1729
Density	Riffle				Run			
	Mean	SE	t Value	Pr > |t|	Mean	SE	t Value	Pr > |t|
OVERALL MODEL SIGNIFICANCE	F=23.19, P<0.0001, Adj-R2=0.8161				F=19.51, P=0.0001, Adj.-R2=0.5528			
Intercept	4.3117	0.2919	14.77	**<0.0001**	2.3628	0.2912	8.11	**<0.0001**
Percent change in turbidity	-0.1163	0.0387	-3.00	**0.0062**	na	na	na	na
Annual peakflow	0.0000	0.0000	-0.21	0.8323	na	na	na	na
Log (average daily discharge)	-0.2575	0.0385	-6.69	**<0.0001**	-0.088	0.0394	-2.22	**0.0345**
No. days below base turbidity (<50 NTU)	1.0919	0.2481	4.40	**0.0002**	0.7763	0.1298	5.98	**<0.0001**
Annual peakflow* No. days below base turbidity	0.0000	0.0000	-1.16	0.2563	na	na	na	na
Log (# days above turbidity threshold of 400 NTU)	0.0828	0.0492	1.68	0.1053	na	na	na	na
Biomass	Riffle				Run			
	Mean	SE	t Value	Pr > |t|	Mean	SE	t Value	Pr > |t|
OVERALL MODEL SIGNIFICANCE	F=12.35, P<0.0001, Adj-R2=0.6541				F=21.26, P=0.0001, Adj.-R2=0.4032			
Intercept	0.3477	0.0542	6.42	**<0.0001**	0.0034	0.0024	1.42	0.1663
Log (average daily discharge)	-0.0361	0.0070	-5.15	**<0.0001**	na	na	na	na
No. days below base turbidity (<50 NTU)	0.1082	0.0481	2.25	**0.0336**	0.0170	0.0037	4.61	**0.0001**
Annual peakflow	0.0000	0.0000	-0.71	0.4821	na	na	na	na
Annual peakflow* No. days below base turbidity	0.0000	0.0000	-0.87	0.3935	na	na	na	na
Log (# days above turbidity threshold of 400 NTU)	-0.0144	0.0096	-1.51	0.1435	na	na	na	na

3.2.2.3.4 Functional Feeding Groups

A measure of the distribution of functional feeding groups provides information regarding the balance of the macroinvertebrate community based on trophic function. Distribution of functional feeding groups is dependent on numerous factors including natural disturbances, various types of pollution, habitat availability and potential for food acquisition. During this study the proportion of functional feeding groups was determined for each habitat and each sampling date (Figures 3-57 and 3-58). In most Colorado streams it is common for the collector-gatherer group to be dominant, although other groups (with the exception of piercer-herbivores) are often well represented. The most noteworthy observation was the high proportion of collector-filterers in the riffle habitat during most late summer and fall sampling events. A departure from this trend was observed on 29 Aug. 2000 and 16 Aug. 2001 (Figure 3-57). Members of the collector-filterer group use a filtering technique or apparatus to capture food particles from the water column. This process requires specific environmental conditions (specific velocity and low levels of suspended inorganic material) to enable the macroinvertebrates to acquire adequate sizes and quantities of food.

3.2.2.3.5 Detritus

Detritus estimates provided in these results are relatively crude because samples were taken using a Hess Sampler. The Hess Sampler is not a preferred method for sampling detritus, however, the sampling method was consistent on all sampling occasions throughout the study. Composition of detritus samples from both habitats included periphyton and other living and non-living organic material. Results of comparisons between the sites suggest that greater quantities of detritus were usually found in riffle habitat (see Appendix B, Figure 29). Levels in riffle habitats were highly variable throughout each season. Trends in detritus levels were not similar when compared among years; however, the detritus levels during each year of sampling followed similar trends as those reported by the macroinvertebrate production metrics.



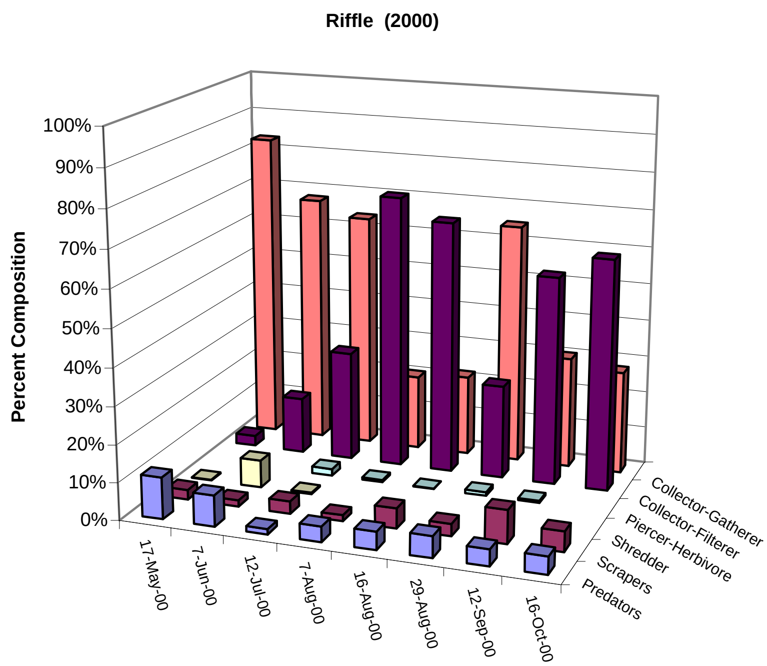
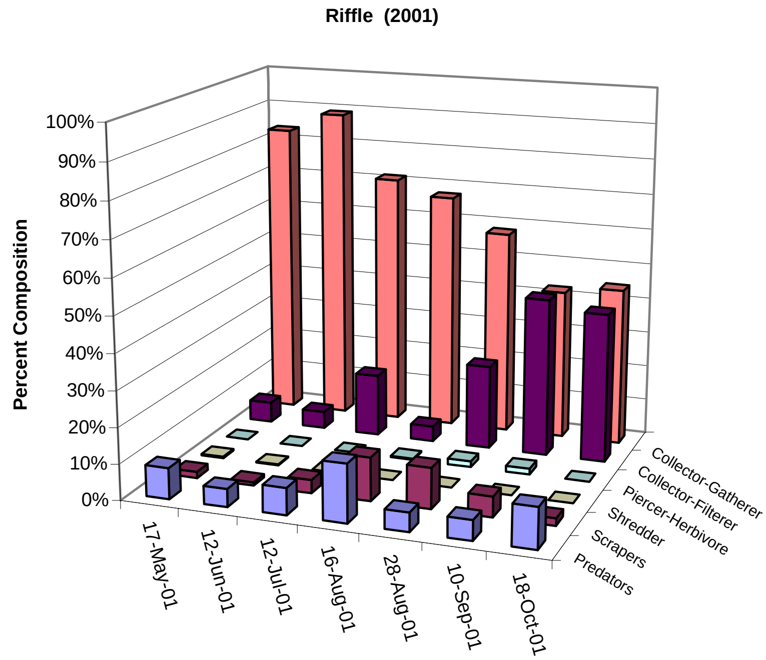


Figure 3-57. Functional Feeding Groups of macroinvertebrates collected from riffle habitat at the Clifton site in the 15-MR of the Colorado River, Colorado.



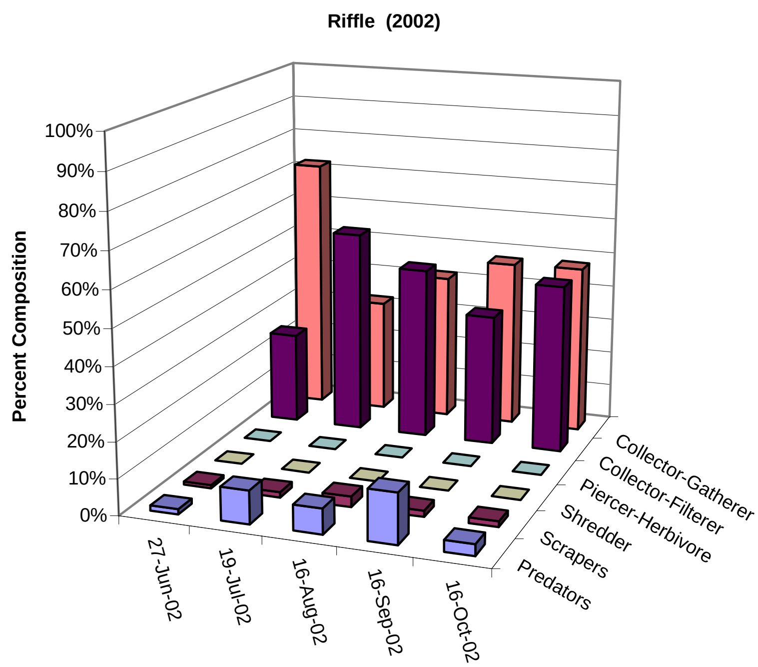


Figure 3-57 (continued). Functional Feeding Groups of macroinvertebrates collected from riffle habitat at the Clifton site in the 15-MR of the Colorado River, Colorado.

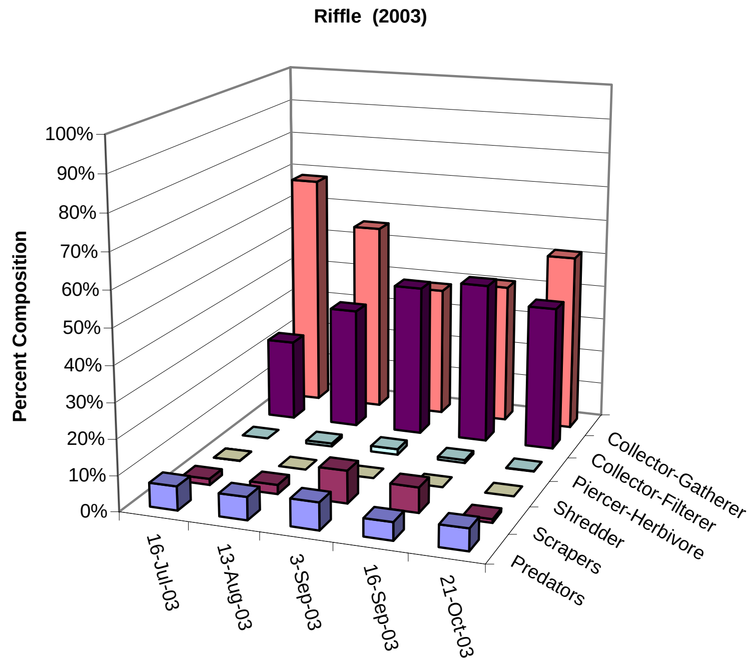
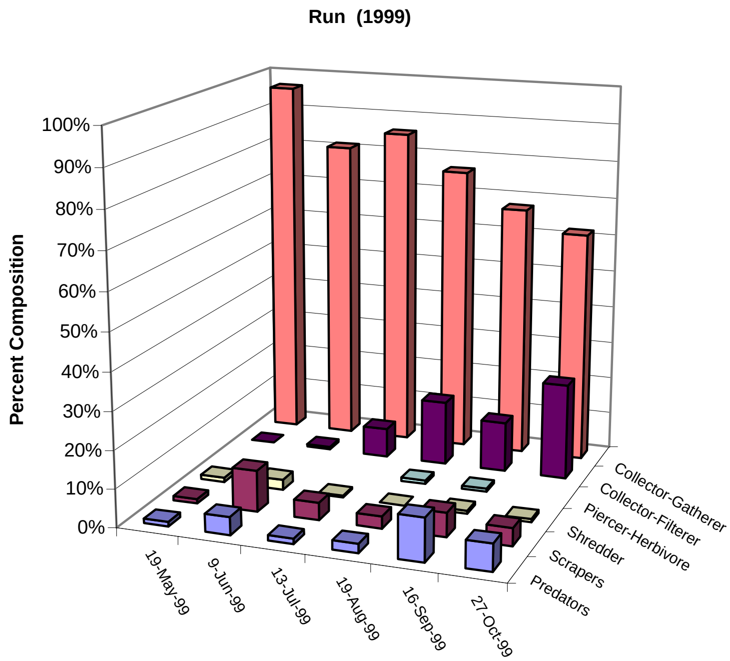


Figure 3-57 (continued). Functional Feeding Groups of macroinvertebrates collected from riffle habitat at the Clifton site in the 15-MR of the Colorado River, Colorado.



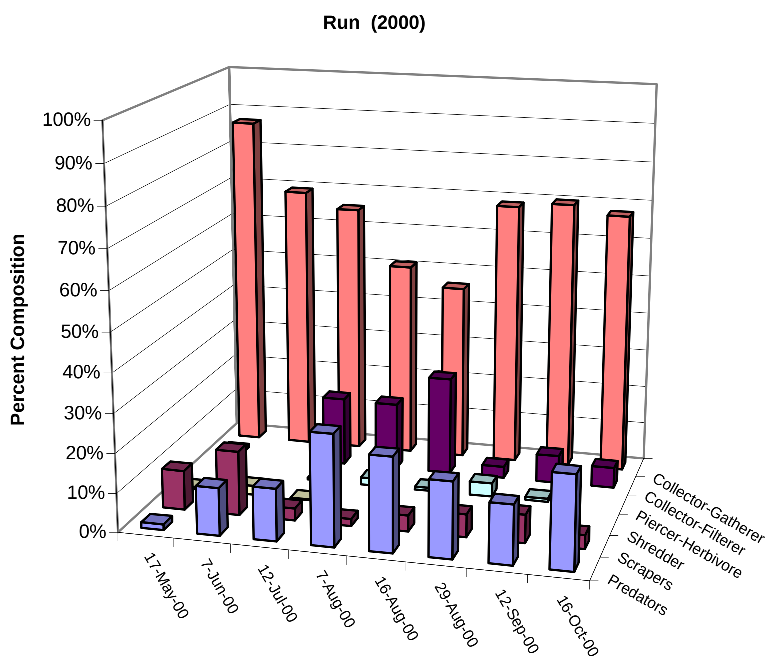
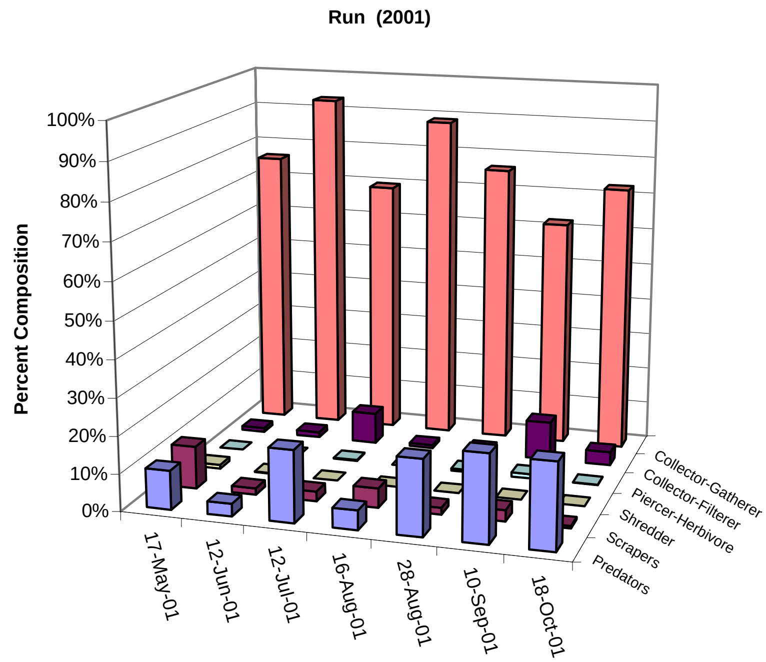


Figure 3-58. Functional Feeding Groups of macroinvertebrates collected from run habitat at the Clifton site in the 15-MR of the Colorado River, Colorado.



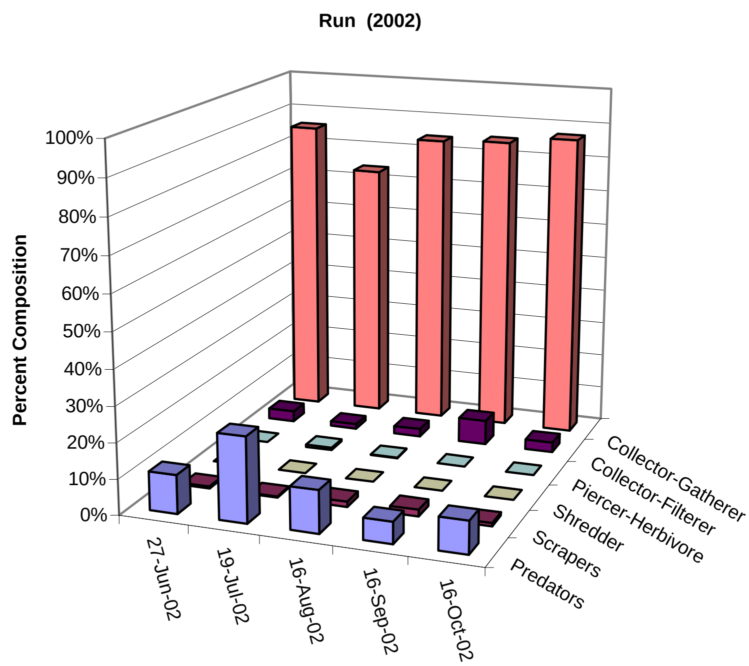


Figure 3-58 (continued). Functional Feeding Groups of macroinvertebrates collected from run habitat at the Clifton site in the 15-MR of the Colorado River, Colorado.

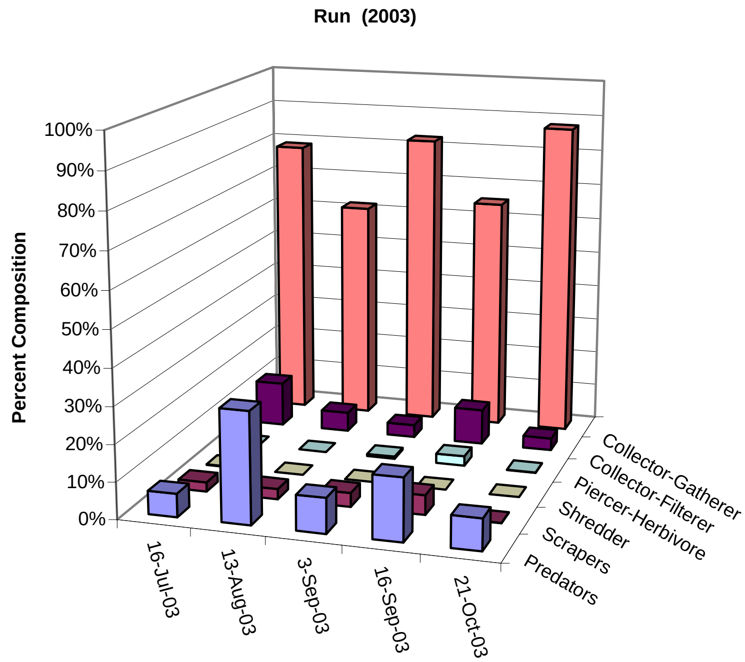


Figure 3-58 (continued). Functional Feeding Groups of macroinvertebrates collected from run habitat at the Clifton site in the 15-MR of the Colorado River, Colorado.

3.2.2.3.6 Synoptic Study Sites

During the 2001 sampling season additional sites were surveyed on three occasions to collect similar data from other reaches of the Colorado drainage, and determine if observations from the Clifton site would be representative of these other reaches. Results of this sampling effort are presented in Appendix B. Metrics used to analyze macroinvertebrate data were summarized and compared between sites (Table 3-10). Site M-46 was a location with higher velocity in the same riffle as the Site 5 transect at the Clifton site. The M-46 site was only sampled for macroinvertebrates. Run habitat was not sampled in May at the synoptic study sites. Metrics used to describe the macroinvertebrate data at the Clifton site were used to describe the data from the expanded site locations.

3.2.2.3.7 Water Quality Metrics

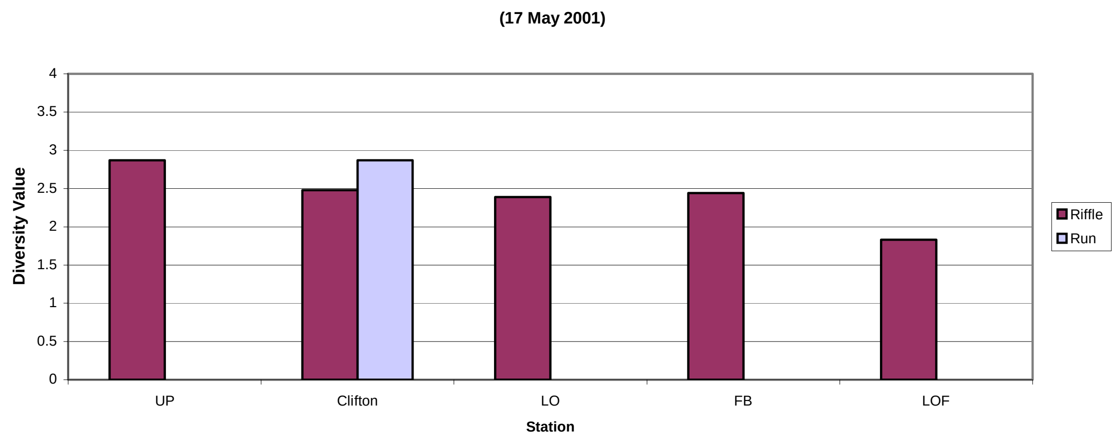
Diversity, Evenness and F.B.I. values were compared between habitats and among site locations on each sampling date (Table 3-10, Figures 3-59, Appendix). Although these metrics are less sensitive to natural changes in habitat, they were reported in order to provide background information and to test for confounding effects from other types of disturbance or pollution. A review of the results obtained from each metric can provide insight into trends observed in the data.

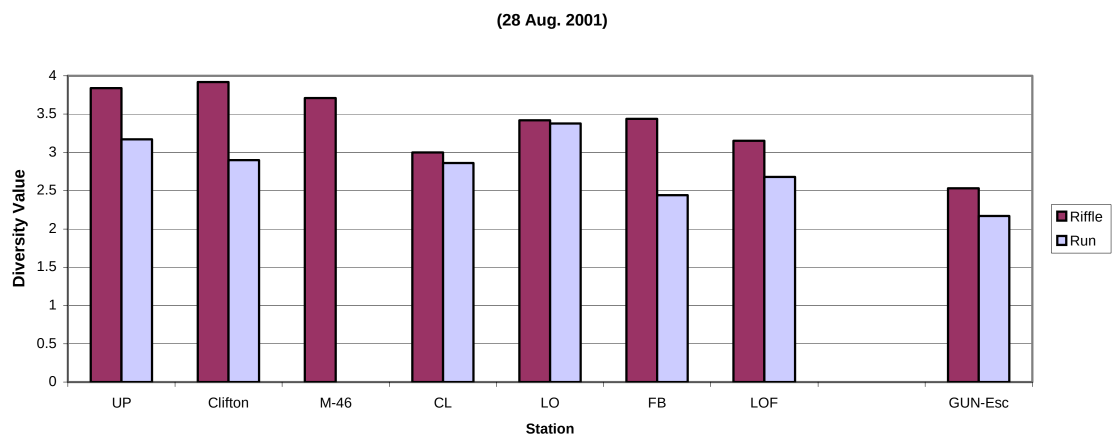
Macroinvertebrate diversity values ranged from 1.03 in run habitat at site LO in October to 3.92 in riffle habitat at the Clifton site in August (Figure 3-59). Diversity values tended to decrease slightly in a downstream direction, and in most instances riffle habitat produced higher diversity values than run habitat. In general, higher diversity values were reported during the month of August.

Evenness values appeared to be closely related to diversity values (Table 3-10). Evenness values ranged between 0.807 and 0.263 during the 2001 sampling events. Highest evenness values and overall best ratings for most sites were produced during August. Lowest evenness value came from the same site and sampling occasion as the lowest diversity value suggesting that a local source of pollution may be influencing aquatic communities. Evenness values were not consistently different

Table 3-10. Metrics and comparative values for macroinvertebrate samples collected from riffle and run habitat in the expanded study area of the Colorado and Gunnison rivers, Colorado.

17 May 01	Diversity		Evenness		F.B.I.		E.P.T.		Richness		Density (#/m^2)		Biomass (g/m^2)	
	Riffle	Run	Riffle	Run	Riffle	Run	Riffle	Run	Riffle	Run	Riffle	Run	Riffle	Run
Site UP	2.87		0.626		5.45		11		24		1764		0.4465	
Clifton	2.48	2.87	0.606	0.775	5.69	5.49	8	6	17	13	1730	368	0.2946	0.2969
Site LO	2.39		0.572		6.43		7		18		1251		0.1323	
Site FB	2.44		0.771		6.21		4		9		291		0.0644	
Site LOF	1.83		0.549		7.53		3		10		575		0.0299	
28 Aug. 01	**Diversity**		**Evenness**		**F.B.I.**		**E.P.T.**		**Richness**		**Density (#/m^2)**		**Biomass (g/m^2)**	
Site UP	3.84	3.17	0.807	0.761	5.05	5.79	13	9	27	18	2129	1193	0.2888	0.1876
Clifton	3.92	2.90	0.784	0.709	4.98	6.72	17	7	32	17	5715	1270	0.8504	0.1024
Site M-46	3.71		0.736		4.44		17		33		8328		1.9148	
Site CL	3.00	2.86	0.590	0.651	4.27	6.00	19	11	34	21	14,285	1791	5.0852	0.1461
Site LO	3.42	3.38	0.677	0.796	4.38	6.11	16	11	33	19	9870	794	1.6870	0.1082
Site FB	3.44	2.44	0.732	0.609	6.06	7.28	10	5	26	16	5992	706	0.8446	0.0495
Site LOF	3.15	2.68	0.688	0.807	7.00	7.27	8	2	24	10	5516	345	0.7457	0.0426
GUN-Esc	2.53	2.17	0.632	0.556	5.05	8.13	5	4	16	15	2413	1649	1.6180	0.2313
18 Oct. 01	**Diversity**		**Evenness**		**F.B.I.**		**E.P.T.**		**Richness**		**Density (#/m^2)**		**Biomass (g/m^2)**	
Site UP	3.32	2.38	0.671	0.562	5.06	5.77	15	8	31	17	10,652	8128	1.1151	0.6214
Clifton	2.71	2.63	0.542	0.657	5.13	6.31	15	6	32	16	18,374	4231	3.9954	0.6916
Site CL	2.67	2.53	0.572	0.567	4.18	5.90	13	10	25	22	35,213	4714	22.944	0.6720
Site LO	3.37	1.03	0.642	0.263	4.58	9.27	18	2	38	15	24,331	4312	11.163	0.4476
Site FB	2.12	1.34	0.437	0.314	6.60	6.45	8	5	29	19	20,268	15,244	2.4166	1.1933
Site LOF	1.75	1.69	0.372	0.444	6.41	7.91	7	3	26	14	22,489	4818	3.5823	0.3728
GUN-Esc	1.83	1.66	0.448	0.436	5.41	6.64	4	4	17	14	13,686	4123	2.4879	0.4258





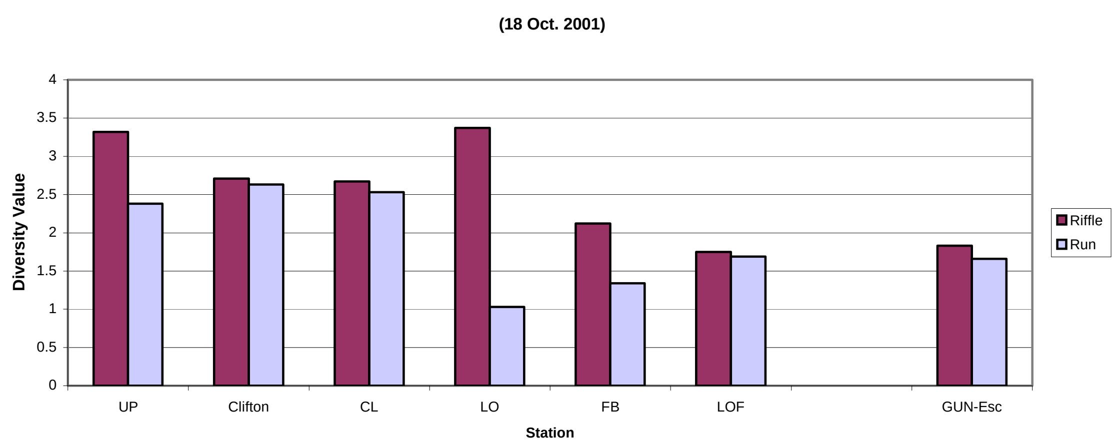


Figure 3-59. Diversity values for macroinvertebrates collected in May (top), August (middle), and October (bottom), 2001 from the Colorado and Gunnison rivers, Colorado.

between the habitat types. In general, the results produced by these metrics provide evidence of some seasonal influence on aquatic communities, and areas possibly affected by pollution or poor habitat within the synoptic study area.

Trends in FBI values were similar to results from diversity and evenness indices. Values appear to increase somewhat in a downstream direction, and on most occasions the influence of nutrients appears to be greater in run habitat as compared to riffle habitat (Table 3-10). The few exceptions to this trend corresponded to sampling events that had less difference in current velocity between habitats. FBI values ranged from 4.18 in riffle habitat at site CL in October to 9.27 in run habitat at site LO in October. Little variation was observed among sampling occasions at sites upstream of LO.

3.2.2.3.8 Richness Metrics

Taxa richness and the EPT index were used to measure the number of identifiable taxa present at each location (Table 3-10, Figures 3-60 and 3-61). Results obtained by these metrics provide information regarding habitat preference and availability at each site, and illustrate spatial changes in community composition that may be related to habitat availability or disturbances within the study area. EPT and taxa richness values ranged from 2 to 19 and 9 to 38, respectively. A spatial trend suggests that a decline in these metric values occurs in the 18-MR and the Gunnison River site. Low values were also reported throughout the study area during May sampling. A more obvious difference is observed when comparing results between habitats (Figures 3-60 and 3-61). Both metrics indicated that a greater number of taxa were in riffle habitat compared to run habitat.

3.2.2.3.9 Production Metrics

Density and biomass were used as an indication of macroinvertebrate production at each site. Results provided by these metrics indicated that production was usually greatest in the riffle habitat (Figures 3-62 and 3-63). The few examples when biomass values were similar between habitats were consistent with sites exhibiting less difference in velocity between habitats. Both metrics indicated that macroinvertebrate production increased throughout the 2001 sampling season.

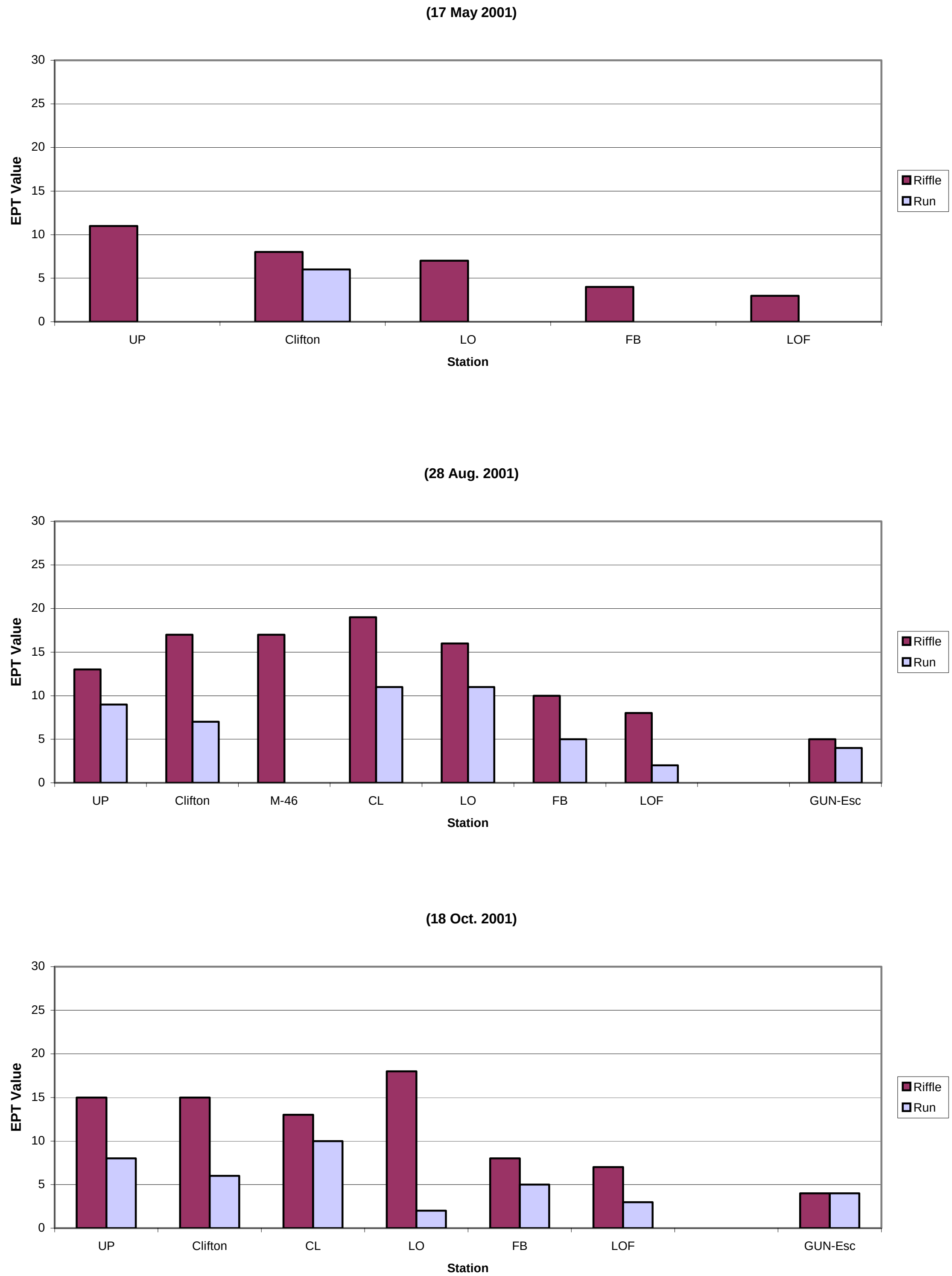


Figure 3-60. EPT values for macroinvertebrates collected in May (top), August (middle), and October (bottom), 2001 from the Colorado and Gunnison rivers, Colorado.

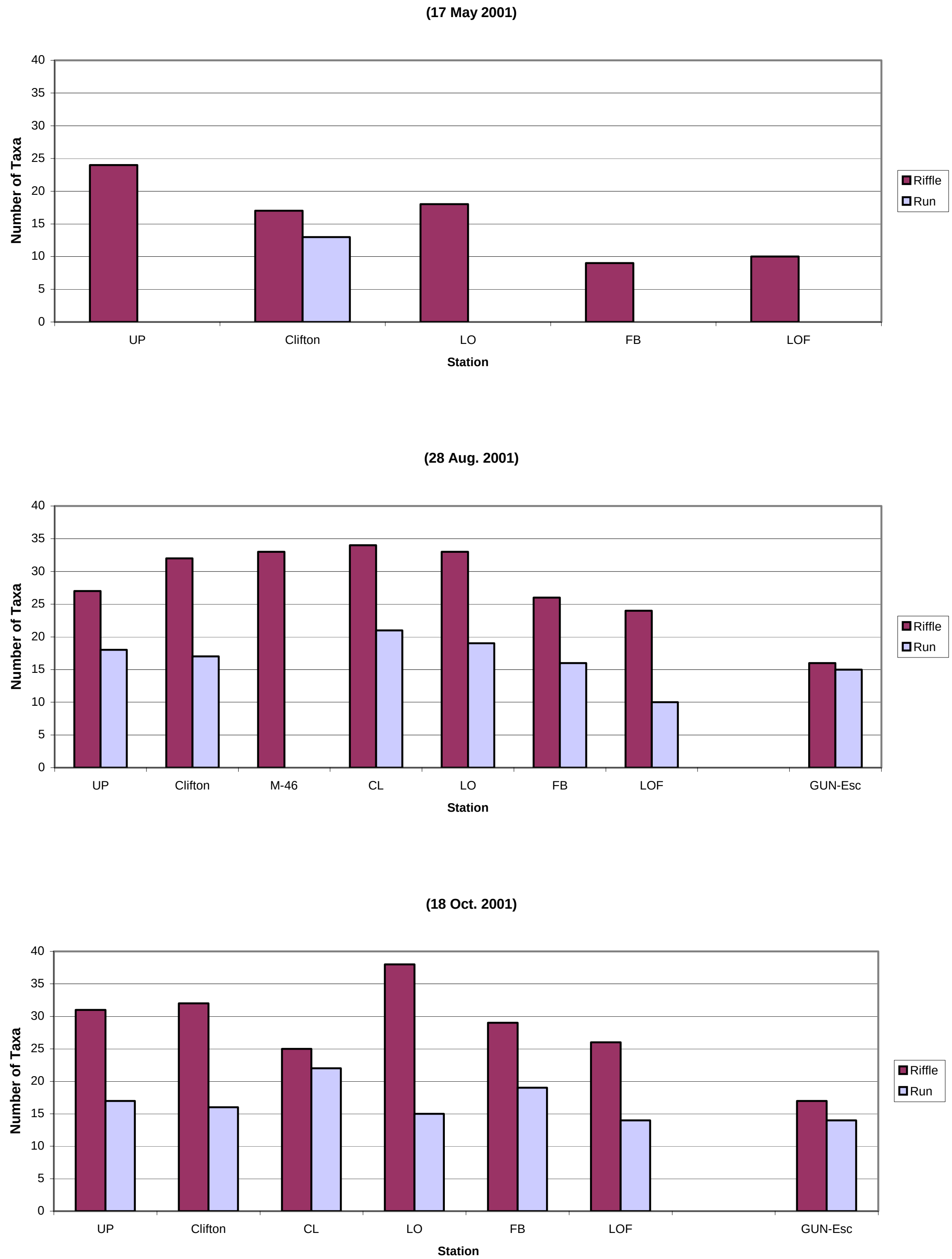
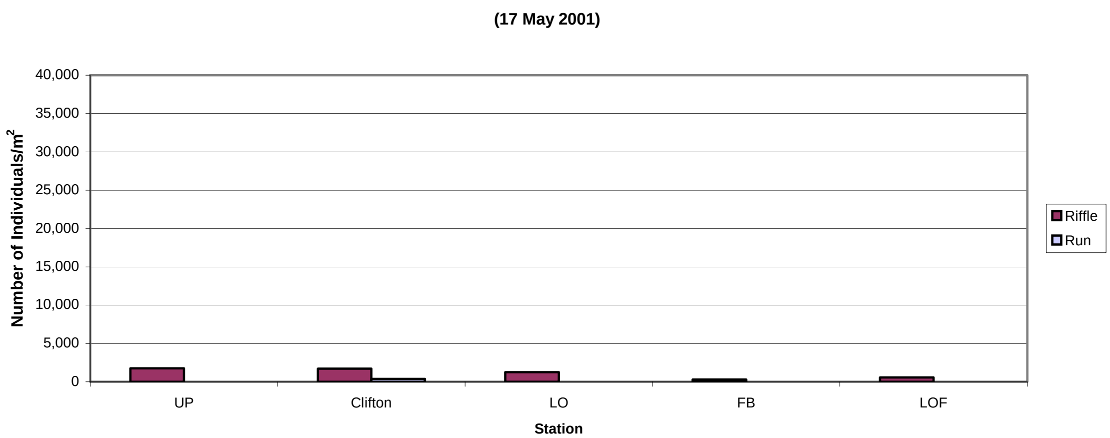
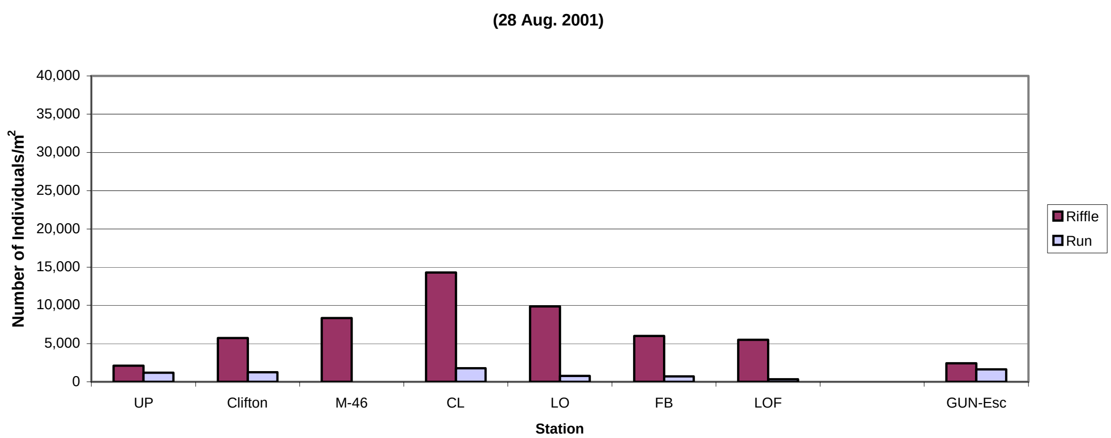


Figure 3-61. Richness values for macroinvertebrates collected in May (top), August (middle), and October (bottom), 2001 from the Colorado and Gunnison rivers, Colorado.





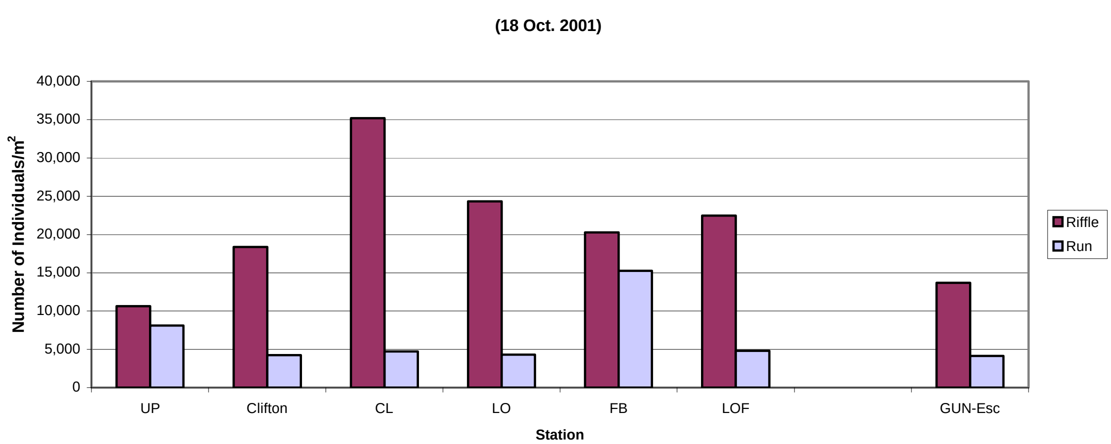


Figure 3-62. Density values for macroinvertebrates collected in May (top), August (middle), and October (bottom), 2001 from the Colorado and Gunnison rivers, Colorado.

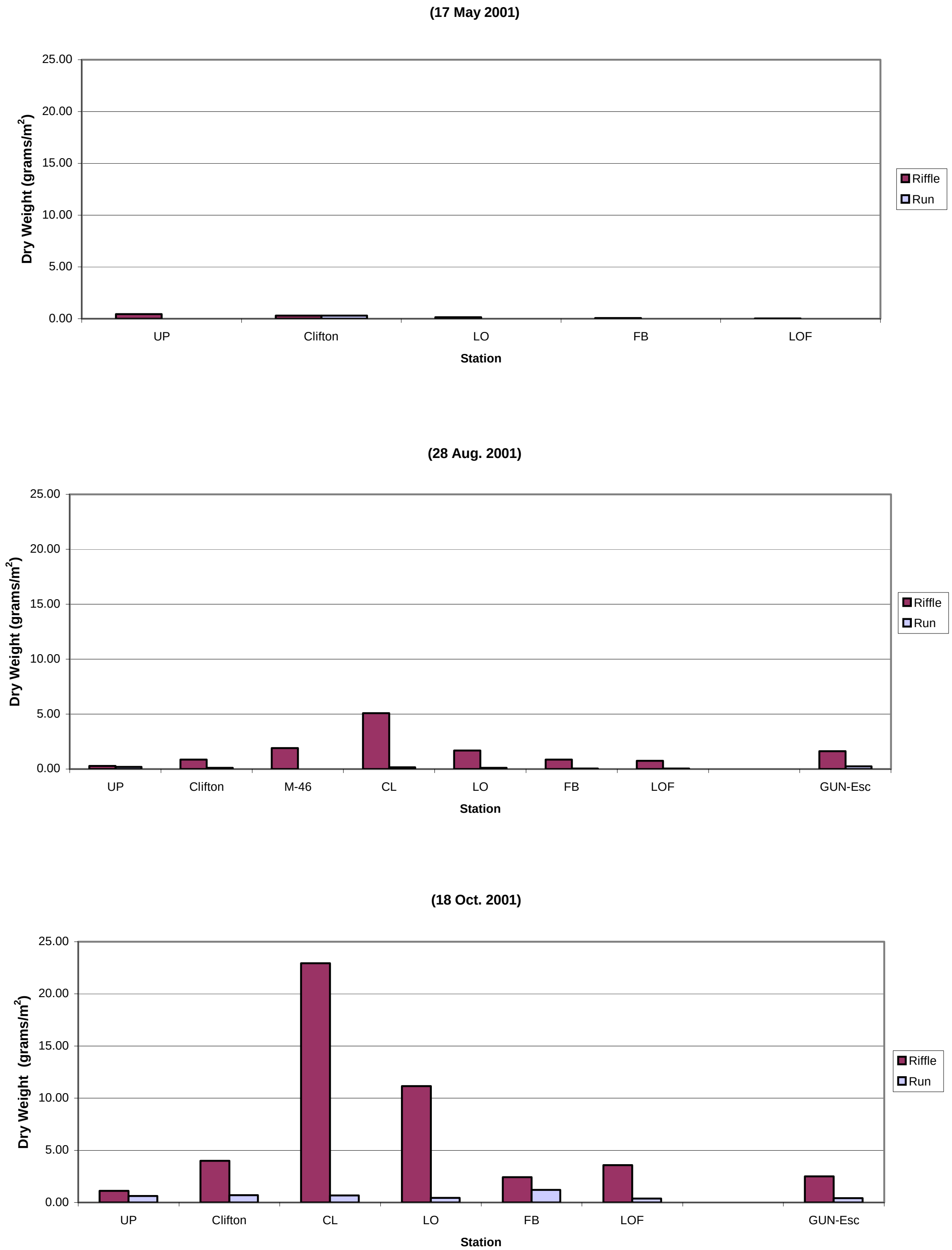
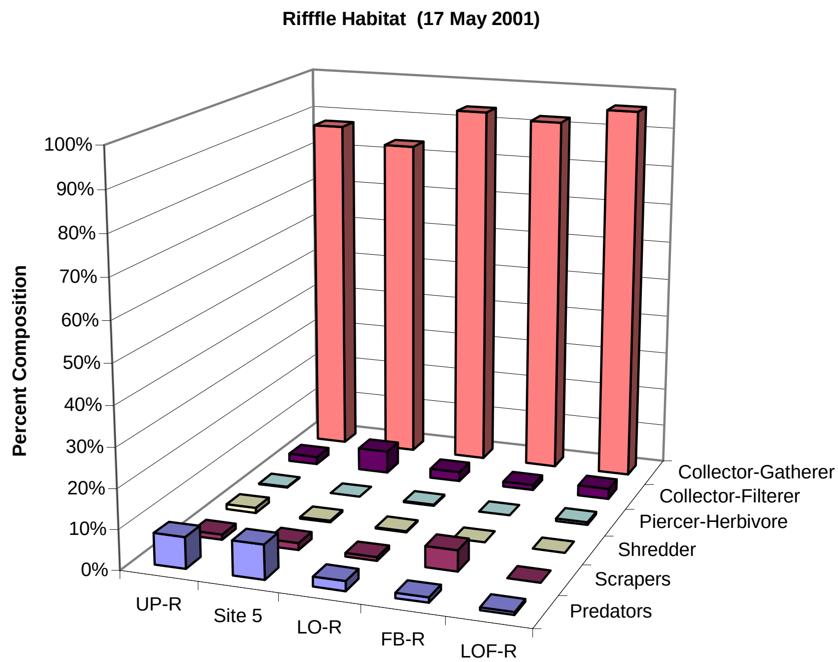


Figure 3-63. Biomass values for macroinvertebrates collected in May (top), August (middle), and October (bottom), 2001 from the Colorado and Gunnison rivers, Colorado.

Highest values for all sites were reported in October, while the lowest values generally occurred in May. During August and October standing crop in riffle habitat was greatest in the middle and lower portions of the 15-MR with lower values in the 18-MR, the upper portion of the 15-MR, and the Gunnison River. No clear trend was observed in data from run habitat.

3.2.2.3.10 Functional Feeding Groups

Distribution of functional feeding groups is dependent on the potential for food acquisition, which is influenced by numerous factors including natural disturbances, pollution, and habitat availability. In this study, the distribution of functional groups was used to gain insight into the impact of sedimentation. During this study the proportion of functional feeding groups was determined for each site and each sampling date. Temporal and spatial changes in macroinvertebrate community function were observed throughout the sampling season. In May, riffle habitat was dominated by collector-gatherers, but a high proportion of collector-filterers were present in most late summer and fall samples (Figure 3-64). The increase in collector-filterers was not consistent among sites and was not observed in run habitat. Run habitat was consistently dominated by collector-gatherers and was poorly represented by other groups (Figure 3-65).



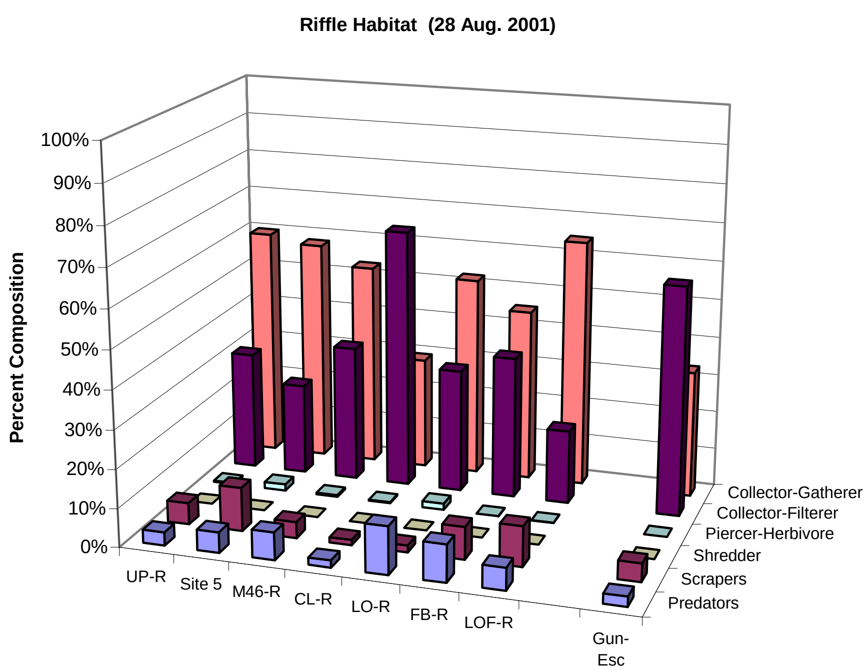


Figure 3-64. Functional feeding groups from riffle habitat in the 15-MR and 18-MR of the Colorado River, Colorado.

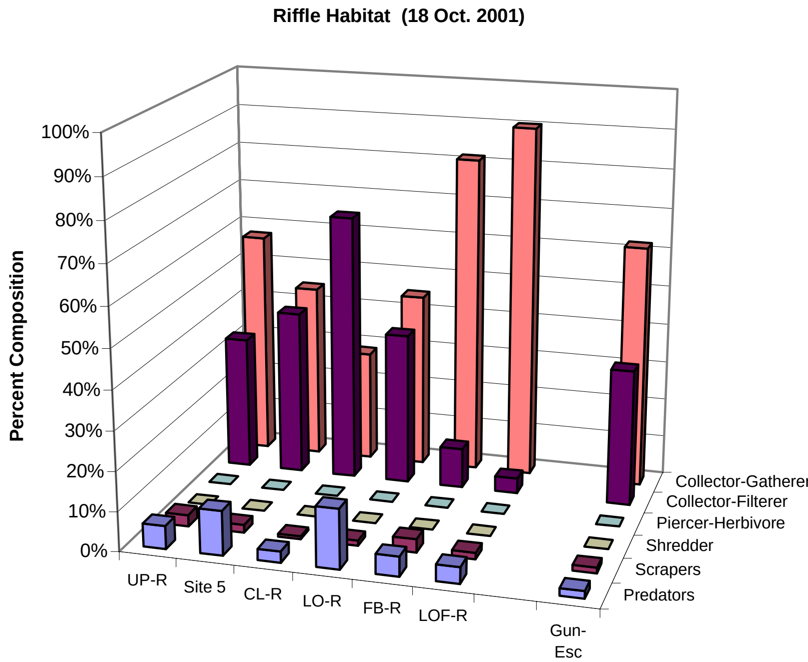
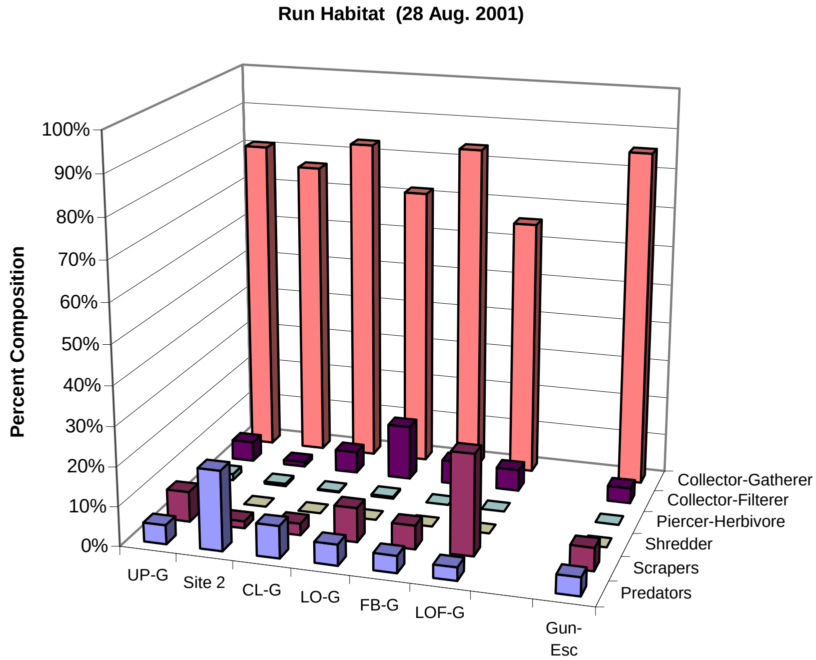


Figure 3-64 (continued). Functional feeding groups from riffle habitat in the 15-MR and 18-MR of the Colorado River, Colorado.



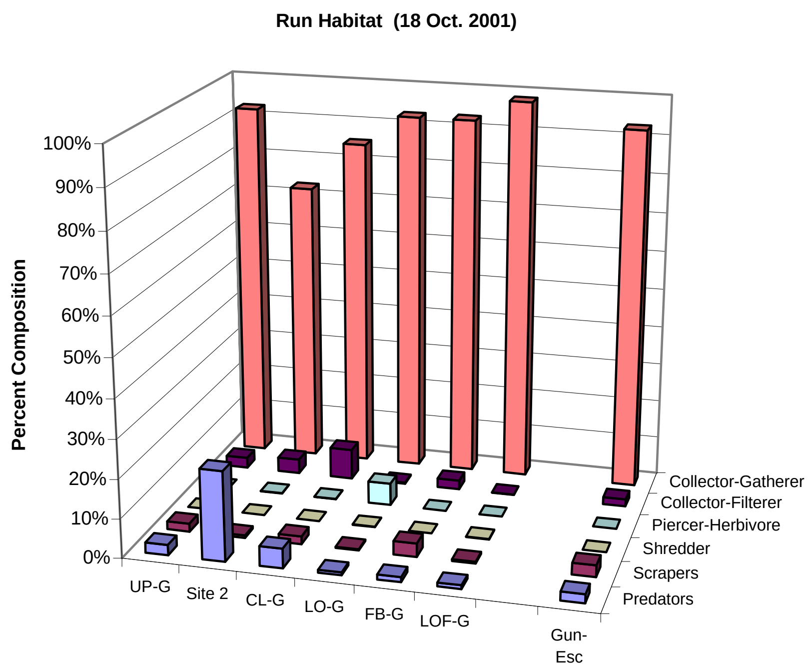


Figure 3-65. Functional feeding groups from run habitat in the 15-MR and 18-MR of the Colorado River, Colorado.

3.2.3 Fish Populations

Fish population estimates were determined for small-bodied species and young (total length < 150 mm) life stages of large-bodied fishes (hereafter both groups referred to as small-bodied fishes) for three riffle and three shoreline run habitats sampled at the Clifton site. The electrofishing technique used in this procedure is particularly effective at removing fish of small size that are often not captured using other electrofishing techniques (e.g. boat electrofishing). Six native species (one native hybrid) and eight non-native species were captured during the sampling effort (Table 3-11). Native fish accounted for approximately 80% of the species composition in riffle habitat and approximately 50% in run habitat (Figures 3-66 and 3-67). Fish populations in riffle habitat were dominated by native speckled dace, which accounted for over 70 percent of the overall population (*N*=865) (Figure 3-66). Populations in run habitats were more evenly distributed with no species accounting for more than 35 percent of the total (*N*=451) (Figure 3-67). Fish density and biomass were highest in riffle habitat compared to run habitat. Density in riffles was more than two times that found in runs and biomass in riffles was approximately four times the biomass found in the run habitats (Table 3-12).

Although specific attempts were not made to capture crayfish, numerous individuals were captured (riffle: 42 [avg. wt. 7.62 g], run: 13 [avg. wt. [4.42 g]) during the sampling. When captured, individual crayfish were removed and weighed and measured. Electrofishing is not an effective technique to capture crayfish. Due to the difficulty in capturing crayfish using this technique and a non-descending removal pattern, a biomass estimate based entirely upon the total number of crayfish captured from each habitat was calculated. Riffle habitat had a crayfish biomass estimate of 1.18 grams per meter^2 and run habitat had an estimate of 0.16 grams per meter^2.

Fish density by habitat type was extrapolated to a biomass per kilometer basis using specific habitat areas from habitat mapping conducted by Lamarra (1999). The amount of each habitat type was approximately 15,500 meter^2 per kilometer (V. Lamarra, pers. communication, Table 3-13). In this analysis the specific run habitat sampled was considered a shoal type run and was not indicative of all run habitat types. The estimated fish abundance and biomass was approximately 69,000 fish per kilometer and approximately 104 kilograms per kilometer (Table

3-14). All of this biomass would be available as a prey source for predatory species (e.g. Colorado pikeminnow).

Table 3-11. Fish species collected in riffle and run habitats in the 15 Mile Reach.

Common Name	Scientific Name	Status
Bluehead sucker	*Catostomus discobolus*	Native
Flannelmouth sucker	*Catostomus latipinnus*	Native
Hybrid sucker	*C. latipinnus* x *C. discobolus*	Native
Mottled sculpin	*Cottus bairdi*	Native
Roundtail chub	*Gila robusta*	Native
Speckled dace	*Rhinichthys osculus*	Native
Common carp	*Cyprinus carpio*	Non-native
Fathead minnow	*Pimephales promelas*	Non-native
Largemouth bass	*Micropterus salmoides*	Non-native
Red shiner	*Cyprinella lutrensis*	Non-native
Sand shiner	*Notropis stramineus*	Non-native
Western mosquitofish	*Gambusia affinis*	Non-native
White sucker	*Catostomus commersoni*	Non-native

Table 3-12. Fish density and biomass in riffle and run habitats in the 15 Mile Reach.

Parameter	Habitat	
	Riffle	Run
Number per meter^2	3.284	1.299
Biomass (grams/meter^2)	5.586	1.438

Table 3-13. Total area by habitat type (Source: Lamarra 1999).

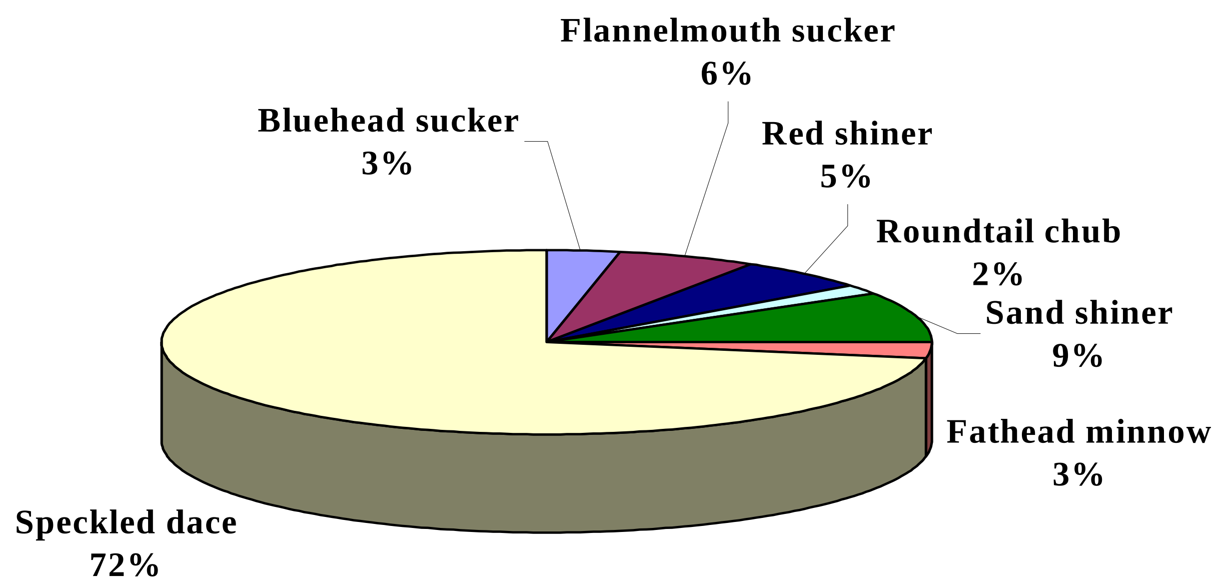
Habitat	Area (m^2 per km)
Riffle	15,500
Run[1]	15,500

[1] – Habitat area based on shoal type habitat presented in Lamarra (1999)

Table 3-14. Total fish abundance and biomass by habitat type.

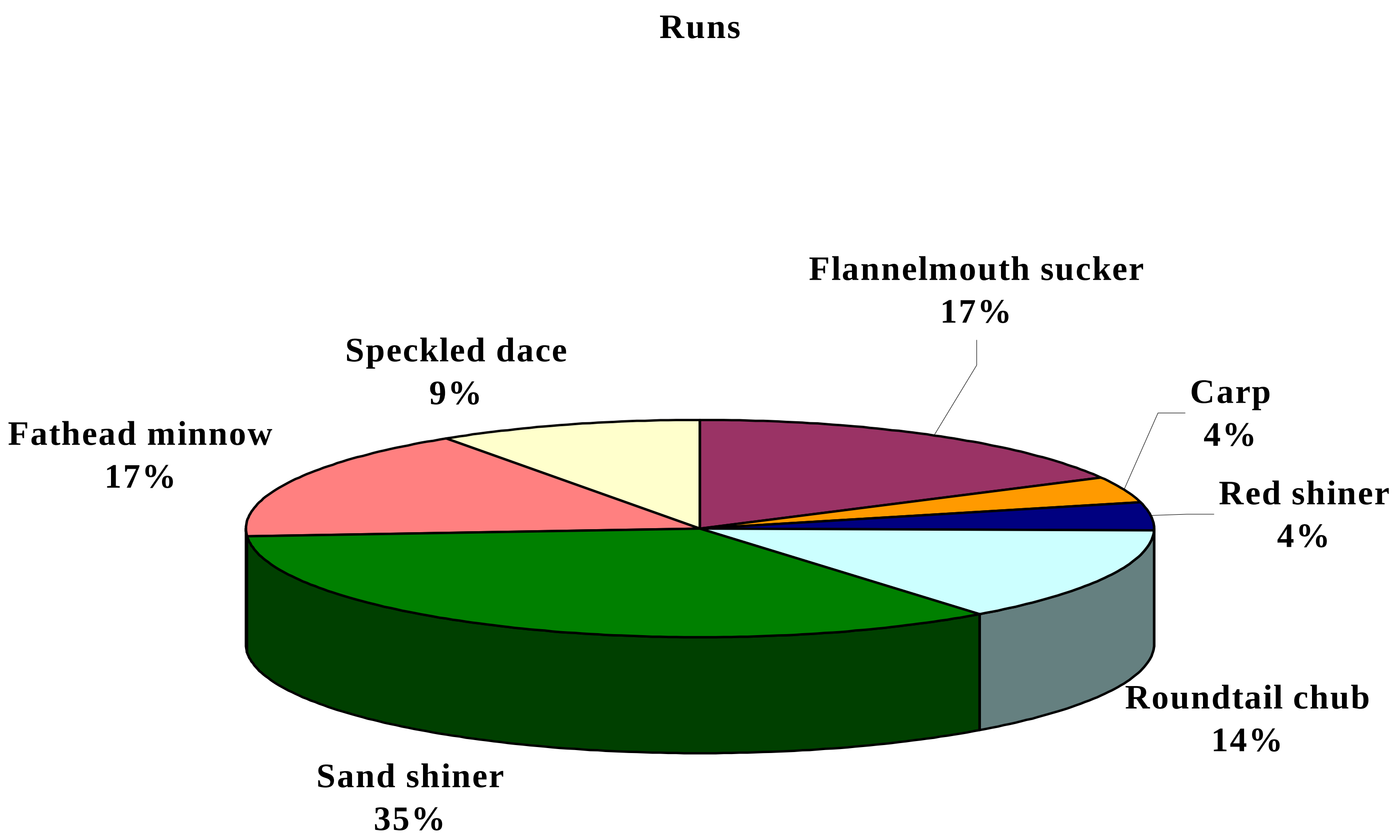
Habitat	Abundance (number/km)	Biomass (kg/km)
Riffle	47,694	82.62
Run (Shoal type)	20,879	21.67
Total	68,573	104.29

Riffles



Note: White suckers, bluehead/flannelmouth sucker hybrids, and mottled sculpin were captured but none accounted for more than 1% of the total catch.

Figure 3-66. Relative abundance of fish captured from riffle habitat in 15 Mile Reach during 2000.



Note: White suckers, bluehead suckers, mosquitofish, and largemouth bass were captured but none accounted for more than 1% of the total catch.

Figure 3-67. Relative abundance of fish captured from run habitat in 15 Mile Reach during 2000.

4 DISCUSSION

Recent recommendations by the USFWS suggested that the productivity of the 15-MR of the Colorado River might be improved by requiring higher peak flows during runoff because peak flows have been reduced by 30-40% since 1950 (Osmundson et al. 1995; Osmundson et al. 2002). A major premise of the plan to increase peak flows is that the high flows will clean the substrate, thereby affording optimum conditions for lower components of the food chain. Osmundson et al. (2002) postulated that Colorado pikeminnow populations are suppressed in some reaches of the Colorado River due to several factors including limited forage fish populations. Osmundson et al. (2002) also acknowledged that periphyton and aquatic macroinvertebrates were important components of the food web for forage fish. Recent research by Lamarra (1999) and Osmundson et al. (2002) supported the hypothesis that higher peak flows will result in greater primary and secondary productivity, thereby indirectly increasing fish condition and carrying capacity. However, these conclusions were based on their study design which incorporated only two years (1994 and 1995) of post-runoff sampling. This study was developed to provide specific and detailed information describing the relationships between physical processes (including peak flows and base flows) and biological productivity over a five-year time span.

4.1 Physical Processes

Investigation of the relationships between flows, sediment loads and habitat requires that the temporal nature of the relationships be recognized and incorporated. In general terms, the annual hydrograph can be divided into low- and high-flow periods (Figure 4-1). The low-flow periods include late-summer and fall baseflows, as well as the winter baseflows that extend from about August to the end of April. The high-flow period includes the rising, peak, and falling limbs of the annual snowmelt hydrograph that usually extend from May to the end of July.

Water-resource development projects in the Upper Colorado River basin upstream of the 15-MR commenced in the 1920s, and by about 1950, approximately 45 percent of the annual streamflow was controlled (Pitlick et al. 1999). Comparison of log-Pearson III flood-frequency curves developed from annual peak flow records at the USGS Palisade gage (No. 090106000) that

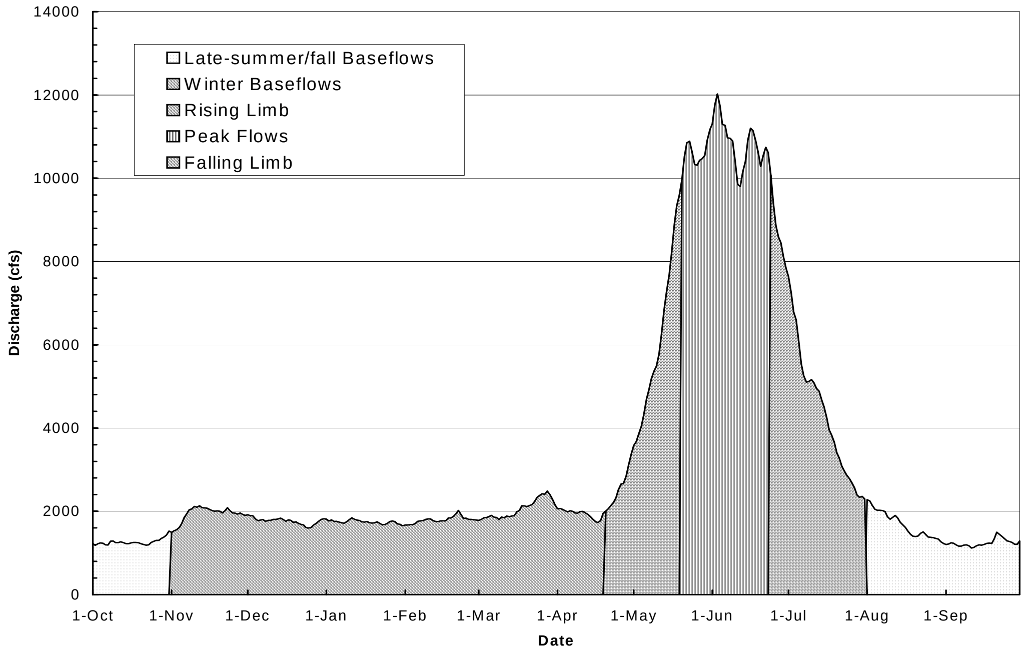


Figure 4-1. Mean annual hydrograph for the Colorado River at Palisade gage showing the subdivisions of the hydrograph discussed in the text.

covered the period from 1902 to 1933 (Figure 3-1), and the USGS Cameo gage (No. 09095500) that covered the period from 1950 to 2000 (Figure 3-2) showed that there has been a 30- to 40-percent reduction in the magnitude of the 2- and 5-year recurrence interval peak flows (Pitlick et al. 1999, and this study). The historic 2-year peak discharge was about 32,000 cfs and the 5-year peak discharge was about 42,000 cfs. The current 2-year peak discharge is about 18,000 cfs and the 5-year peak discharge is about 27,000 cfs.

Suspended-sediment concentrations at the UCR gages have not changed appreciably (Pitlick and Wilcock 2001) as a result of the upstream dam construction in the last 50 years because of the large supply of sediment from the lower elevation portions of the basin that are underlain by highly erodible sedimentary rocks (Iorns et al. 1965; Van Steeter and Pitlick 1998; Liebermann et al. 1989; Spahr et al. 2000). However, suspended-sediment loads in the Colorado River were higher prior to 1940, primarily as a result of widespread arroyo incision that commenced in the mid 1800s (Thompson 1982, 1984; Gellis et al. 1991). Even though the sediment concentrations have remained relatively constant, total sediment loads in the 15-MR have been reduced because of the reduced flows (Pitlick and Van Steeter 1998). Reductions of the peak-flow magnitudes and reduced suspended-sediment loads have caused a 10- to 15-percent reduction in average channel width, and about a 25-percent reduction in side channels and backwaters (Van Steeter and Pitlick 1998; Pitlick and Van Steeter 1994; Pitlick et al. 1999). Regardless of the changes in hydrology and sediment supply, Pitlick et al. (1999) concluded that the current channel morphology is in equilibrium with the current peak flow regime and suspended-sediment load, and therefore, it can be concluded that there are unlikely to be further channel adjustments if the present peak-flow regime is maintained. Based on the morphology of the Clifton site, it is highly unlikely that the width of the river has changed because the left bank is composed of Mancos Shale outcrop, and the right bank is erosional.

The bulk of the annual sediment load is transported during the high-flow period when both the suspended load and bedload is transported (Pitlick et al. 1999) (Figure 4-2). The peak flows are, therefore, both morphologically and biologically important (Power 2001). Pitlick et al. (1999) computed a reach-averaged critical discharge of about 10,000 cfs, and a discharge of about 22,000 cfs for general bed mobilization. However, because flow-sediment-habitat relations generally occur at meso- and micro-scale levels, generalized reach relations do not fully represent important ecological considerations (Downes et al. 1997). Because of the effects of summer thunderstorms, suspended-sediment concentrations can be higher during the low-flow periods (Figure 3-38). The quantity of sand, silt, and clay that is transported during the low-flow periods is relatively small, is dominated by silt and clays, and is morphologically unimportant but it is biologically very important. However, because of the stochastic nature of the thunderstorm events that generate the fine sediment, the events are not well represented in the USGS Cameo gage record that is based on fixed-interval sampling.

The behavior of the physical system can be divided into two somewhat separate, but interconnected, response regimes, framework responses, and transient responses (Figure 4-3). Both have the ability to affect the biological productivity of the system by producing physical disturbances that affect both periphyton and macroinvertebrate trophic levels (Hildrew and Townsend 1987; Biggs et al. 1998a). Framework responses are related to mobilization of the gravels and cobbles that form the bed of the river, and provide the habitat for the periphyton and macroinvertebrates (Biggs et al. 2001). In the context of the Clifton site, incipient conditions for the bed armor layer (D_{50} about 80 mm) occur at snowmelt runoff discharges that exceed

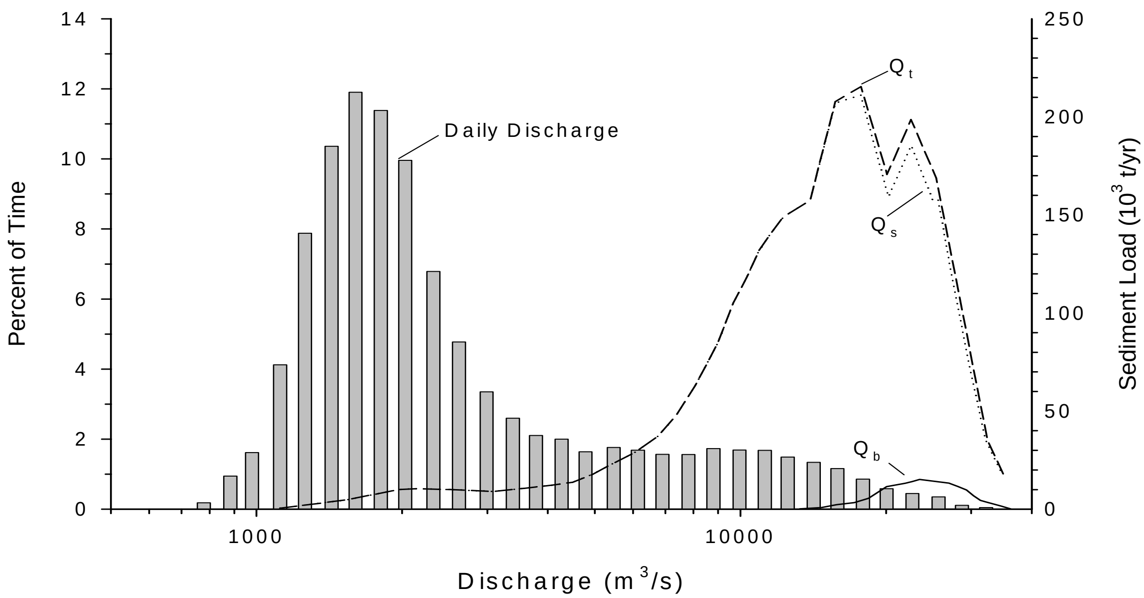


Figure 4-2. Summary of annual sediment loads at the Palisade gage. Q_t represents the total load, Q_s represents the suspended load, and Q_b represents the bedload (modified from Pitlick et al. 1999).

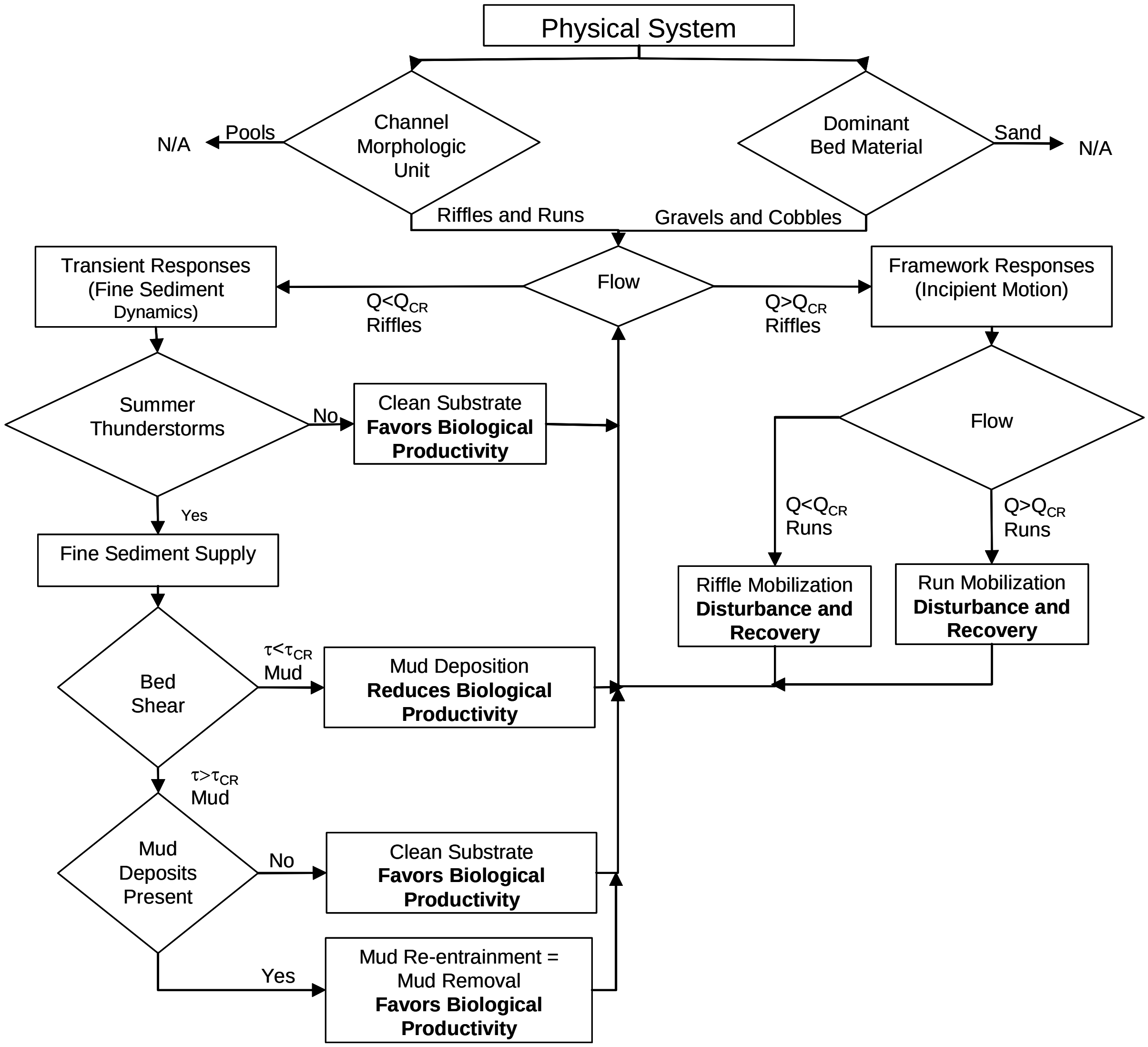


Figure 4-3. Flow chart that summarizes the physical processes that are related to sediment mobilization and mud deposition that create biological disturbances in the 15-MR.

approximately 4,800 cfs (less than a 1-year recurrence interval) in the riffles and about 13,000 cfs (about 1.6-year recurrence interval) in the runs. Mobilization and transport of the run and riffle sediments at discharges greater than 20,000 cfs (2.8-year recurrence interval) create a substantial disturbance to and reset of both the periphyton and macroinvertebrate habitat. Following mobilization of the bed material during the snowmelt runoff period, a new armor layer is formed on the bed of the river in both the riffles and the runs, and provided that the subsequent post-runoff discharges are less than about 4,800 cfs, the armor layer will be stable throughout the site.

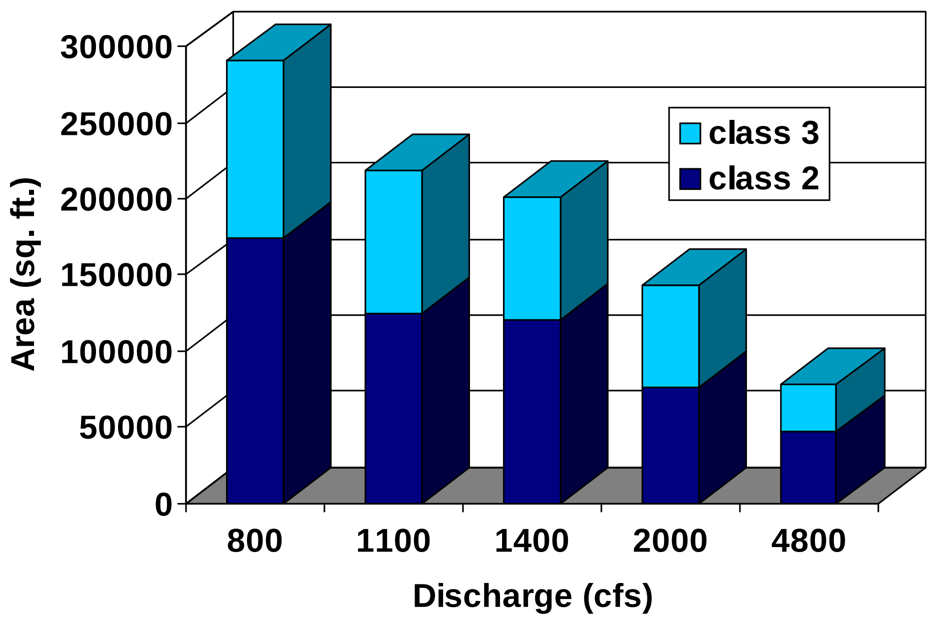
Transient responses (Figure 4-3) are primarily related to the fine sediments (mud) (D_{50} less than 0.06 mm) that is deposited on, and eroded from, the stable gravel-cobble riverbed at different locations in the site when discharges in the river are less than about 4,800 cfs (discharge that is equaled or exceeded about 15 percent of the time). Fine sediment is supplied during post-runoff summer thunderstorms over the lower elevation portions of the basin upstream of the 15-MR that are underlain by highly erodible, sedimentary rocks. Discharges in the river during this period (baseflows) are controlled by upstream reservoir releases and irrigation diversions, and generally range from about 800 cfs (discharge that is equaled or exceeded 90 percent of the time) to 1,200 cfs (discharge that is equaled or exceeded 80 percent of the time). During events when fine sediment is supplied to the reach, mud is deposited on the gravel and cobbles in areas where velocity and shear stress are less than about 2.5 fps and 0.03 lb/ft^2, respectively. At locations where velocity and shear stresses are higher than 2.5 fps and 0.03 lb/ft^2 respectively, mud is not deposited even when there is a supply of fine sediment, and previously deposited mud is re-entrained (Chow 1958; Smerdon and Beasely 1961; Partheniades 1965; Graf 1971; Partheniades and Kennedy 1973; Haralimpedes et al. 2003). Because the shear stress and turbulence are generally higher in riffles than runs, riffles tend to be more sensitive to small changes in discharge than runs. Removal of previously deposited mud may occur in the riffles during small increases in discharge associated with the summer thunderstorms. However, the fine sediments may still affect periphyton and macroinvertebrate communities by abrasion or scouring.

The results of the 2-D modeling were used to determine the surface area (ac) for the individual mud classes, and hence potential habitat for periphyton and macroinvertebrates, within the modeled boundaries of the Clifton site for a range of discharges between 800 and 4,800 cfs

(Figure 4-4). The total submerged area of the site increases from 12.8 ac at 800 cfs to 15.7 ac at 4,800 cfs. At 800 cfs, about 35 percent of the site is relatively mud-free (i.e., shear stress>0.03 lb/ft^2), and the majority of the mud-free area is located in the riffles and the middle of the runs (Figure 3-39). At discharges of 1,100 and 1,400 cfs, about 47 to 54 percent of the site is relatively mud-free, but the mid-channel bar, channel margins, and the margins of the lower run have the potential to contain substantial amounts of mud because the shear stress at these locations is < 0.03 lb/ft^2. At a discharge of 2,000 cfs, about 67 percent of the site is essentially mud-free, with most of the potential for mud deposition occurring on the margins of the channel and the mid-channel bar (Figure 3-42). About 85 percent of the site is mud-free at a discharge of 4,800 cfs (Figure 3-43).

The results of the 2-D modeling can be used to evaluate the potential impacts of flow regime changes on available habitat for periphyton and macroinvertebrates (Figure 4-4). USGS gage records for the Cameo gage extend back to the early 1930s. Using the StateMod v.8.29 (1999) model, the CWCB has developed mean monthly undepleted flow estimates for the Cameo gage from 1934 to 1996. To evaluate the changes in flow regime, since the significant water development projects were emplaced after the 1940s, a comparison between the mean monthly gaged flows and the computed undepleted flows was developed for the period from 1950 to 1996. (Figure 4-5). The Cameo gage record, however, cannot be used to directly evaluate the effects of changed flow regime on the 15-MR because there are significant diversions (about 2,260-cfs diversion capacity) between the gage and the 15-MR. CWCB has not computed the undepleted flows for the Palisade gage because of the short period of record (1991-2002).

For the purposes of this study, a longer term record of depleted flows for the Palisade gage was approximated by computing the difference in flow volume between the two gages on a mean monthly basis for the overlapping period of record (1990-2002; Figure 4-6), and subtracting the differences in the mean monthly recorded values at the Cameo gage for the longer period of record (1950-1996; Figure 4-7). The undepleted mean monthly flows for the Plateau Creek gage were added to the Cameo gage record to provide an undepleted record for the Palisade gage.



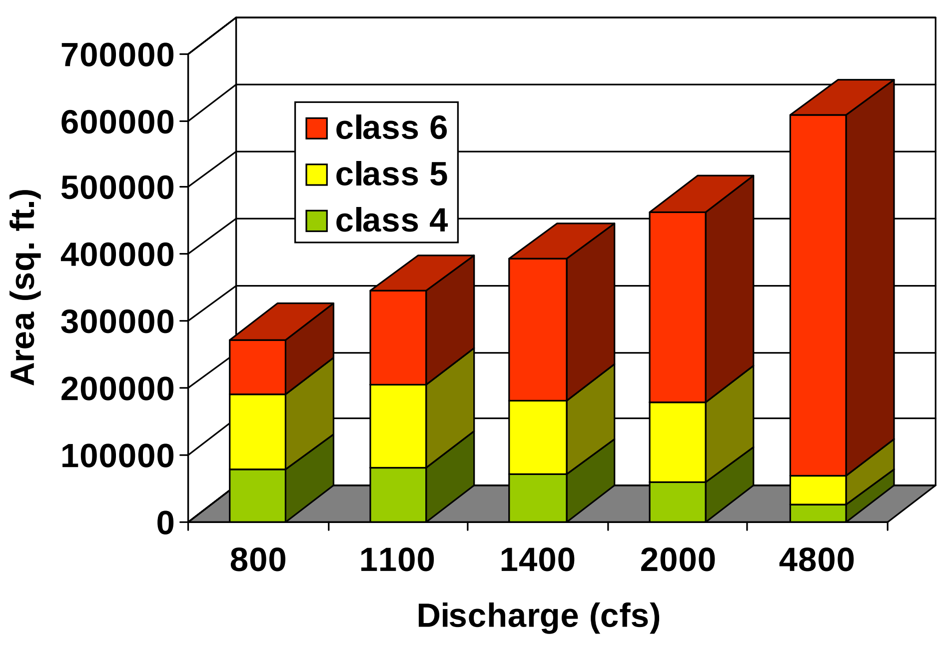


Figure 4-4. Bar graphs showing the areas occupied by each of the mud classes at discharges of 800, 1,000, 1,400, 2,000, and 4,800 cfs at the Clifton site.

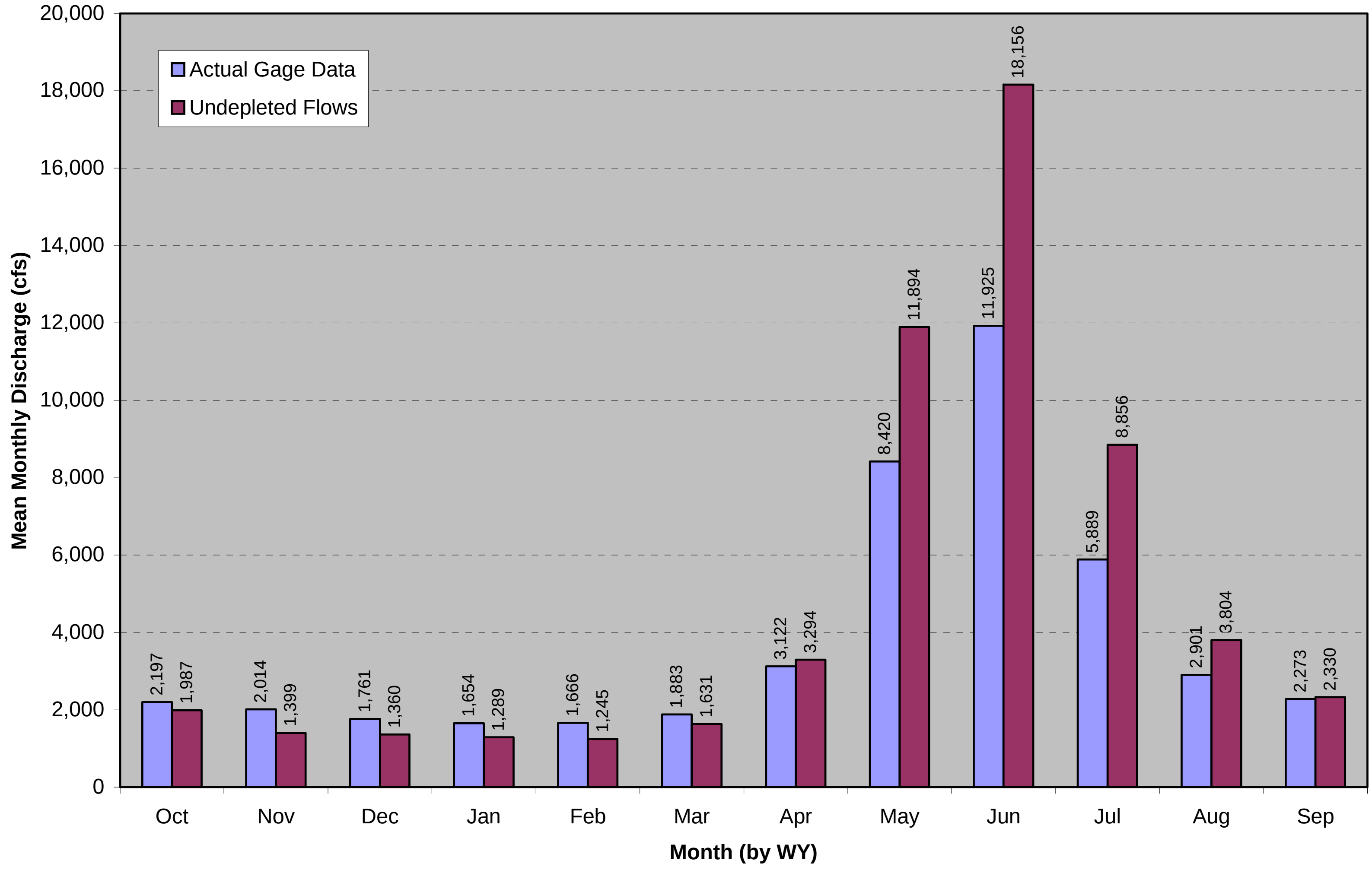


Figure 4-5. Comparison of mean monthly gaged and computed undepleted flows for the Cameo gage from 1950-1996 (undepleted flow data provided by CWCB).

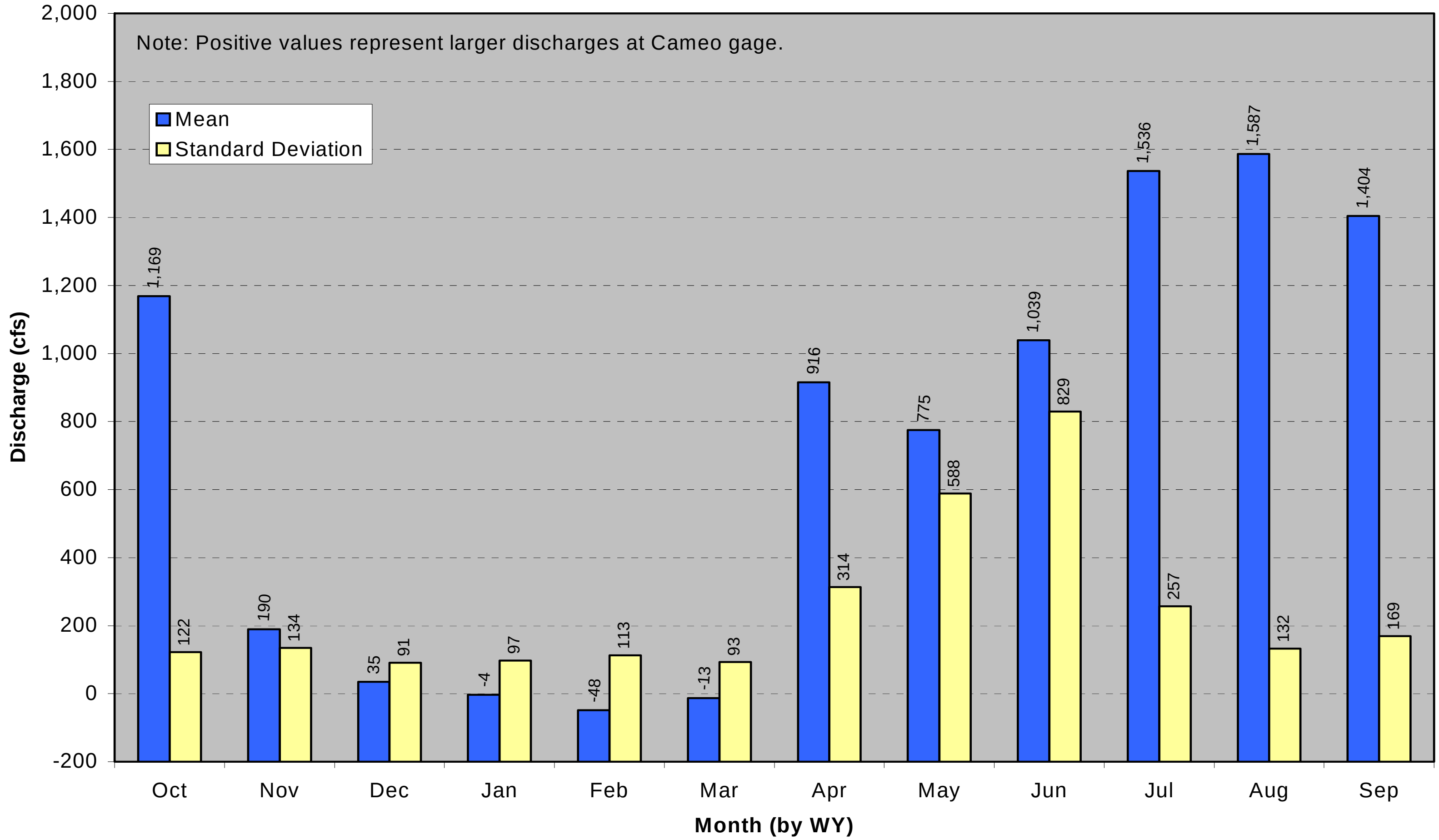


Figure 4-6. Summary of the differences in mean monthly flows between the Cameo and Palisade gages for the overlapping period of record (1990-2002).

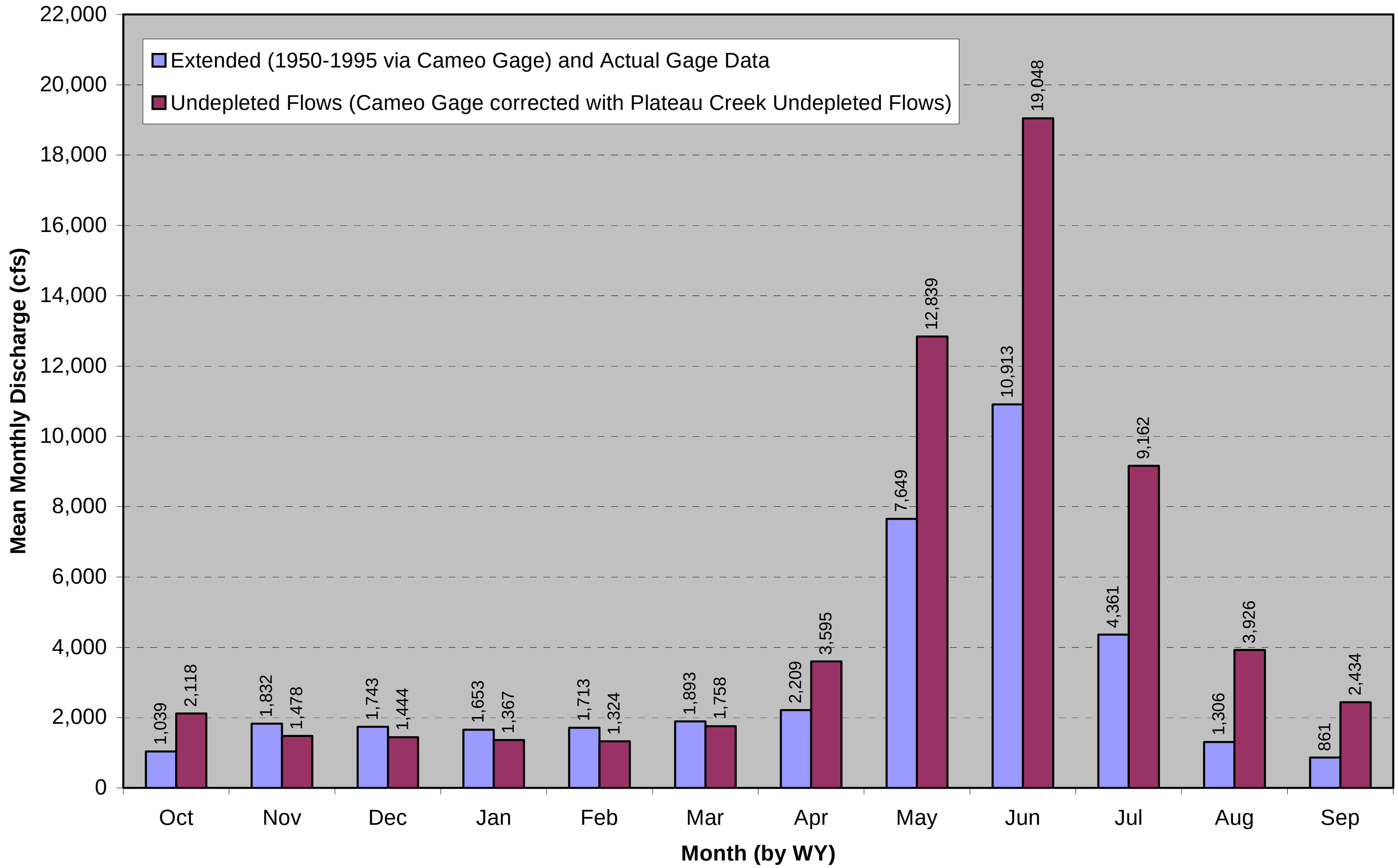


Figure 4-7. Comparison of mean monthly estimated gaged and computed undepleted flows for the Palisade gage from 1950-1996 (undepleted flow data provided by CWCB).

The effects of upstream storage during the snowmelt runoff season (May-July) are very evident in Figure 4-7. The reduced peak flows limit the potential for general bed mobilization in the runs at the Clifton site during the month of June, but bed mobilization still takes place within the riffles at flows in excess of about 4,800 cfs, which occurs commonly during the snowmelt-runoff period. Reduced peak flows, therefore, have reduced the potential for framework gravel-cobble mobilization and flushing of framework fines in the runs at the Clifton site. However, the absolute magnitude of the reduction is not readily determinable because of the imprecision introduced by the use of the mean monthly flows.

From a transient response perspective, the reduced mean monthly flows in the summer-fall baseflow period (August-October) may be more substantial because of the effects of fine sediment (mud) on the biota. In August, the mean monthly undepleted flow is about 3,900 cfs, and the present mean monthly flow is about 1,300 cfs. Based on the 2-D model results, if fine sediment-producing events have occurred, the potential mud-free (classes 4,5, and 6), and hence biologically productive area is about 8.7 ac under the current flow regime and about 11.5 ac under the undepleted flow regime, which is about a 24-percent reduction. In September, the mean monthly undepleted flow is about 2,400 cfs and the present mean monthly flow is about 860 cfs. Based on the 2-D model results, this represents a mud-free area of about 9.6 ac under the undepleted flow regime and an area of about 5.5 ac under the present flow regime, which represents a 43-percent reduction. In October, the mean monthly undepleted flow is about 2,100 cfs and the present mean monthly flow is about 1,000 cfs. Based on the 2-D model results, this represents a mud-free area of about 9.2 ac under the undepleted flow regime and an area of about 6.9 ac under the present flow regime, which represents a 25-percent reduction.

In the winter-spring baseflow period (November-April), the current flows are, with the exception of the month of April, higher than the undepleted flows (Figure 4-7). For the months of November through March, the current flows increase the amount of mud-free area from 3 to 7 percent over the undepleted flow regime. However, in April, the current flows have about 10 percent less mud-free area than the undepleted flows. Given that there are a number of precipitation-induced elevated turbidity events during the winter baseflow period (Figure 3-17); it is likely that the increased flows provide an increased area of mud-free substrate for the biota over what would have been present historically during this component of the annual hydrograph.

4.2 Biological Investigation

Unlike previous research on the 15-MR, this multi-year study depended on frequent sampling of periphyton and macroinvertebrates to monitor primary and secondary standing crop in two different habitat types throughout the snowmelt runoff and summer base flow season. This approach provided an opportunity to assess the influence of peak flows and other variables that are expected to influence periphyton and macroinvertebrate communities from May through October. Benthic communities in the Colorado River evolved to depend on predictable seasonal changes. Seasonal changes include change in day length, discharge, and water temperature. The results of this study suggest that it is the transient events (events that occur stochastically) that influence much of the biological standing crop in this section of the Colorado River.

Extensive biological sampling of riffle and run habitat produced results that varied considerably between habitats and among years. Variability in benthic communities between habitats can be attributed to specific habitat preferences, habitat requirements and the availability of preferred physical conditions at each site. The data suggests that variability among years is a function of changes in physical processes (flow velocity, turbidity, sediment deposition, etc.) that result in alteration of specific habitats. The processes that were most often responsible for altering these biological communities were not associated with peak flows, but were usually a product of increased turbidity following thunderstorm events from mid summer into fall.

4.2.1 Periphyton (Clifton Site)

Given optimal conditions periphyton communities should have predictable responses to seasonal influences (length of daylight hours, change in discharge, temperature, etc.) within the confines of habitat limitations. Periphyton growth was expected to be greatest during the warm summer months. An important objective of this study was to determine if seasonal influences (particularly magnitude of peak flow) were responsible for structuring periphyton communities. Results of quantitative sampling were evaluated with the intent of identifying the processes that were most responsible for structuring periphyton communities.

Interpretation of periphyton data was difficult because samples were highly variable. This is a common problem with periphyton sampling in streams (Korte and Blinn 1983). This "patchy" distribution of periphyton communities can be the result of inconsistent substrate material, exposure to light, specific current velocity, and other factors that influence microhabitats.
In most streams, periphyton growth is a function of current velocity and nutrient availability (Horner and Welch 1981). Locations with greater current velocities usually have higher rates of exposure to nutrients. Higher rates of nutrient renewal associated with riffle habitat are more conducive to greater densities of periphyton. The potential for periphyton growth tends to increase with velocity to the point where densities decrease as a result of frictional shear forces (Horner and Welch 1981).

Periphyton growth is less predictable in natural streams where it is exposed to changing velocities and fluctuating concentrations of suspended sediments. The presence of suspended sediment has been found to impact periphyton communities by increasing turbidity (resulting in a decrease in light penetration), and removing periphyton by a frictional scouring process (Newcombe and MacDonald 1991; Allan 1995). The deposition of fine sediments on periphyton communities is suspected to have a smothering effect (Waters 1995), and decrease the nutritional value of periphyton by increasing the inorganic content (Graham 1990; Swift-Miller et al. 1999). There is also evidence that suggests that low concentrations of suspended sediments and sediment deposition may result in an increase in periphyton growth by providing additional nutrients (Cordone and Kelley 1961). Horner et al. (1990) found that loss rates of periphyton were stable during stable velocities, but increased by an order of magnitude or more, in response to sudden increases in velocity. The greatest increase in loss rates occurred after a sudden increase in velocity combined with the addition of suspended solids. These conditions are likely to occur in the 15-MR as a result of summer thunderstorms, and the results of this study confirm that both variables are important influences on periphyton communities.

Linear regression models were developed for density and taxa richness using the parameters that best explained variation in these metrics. Regression analysis indicated that average daily discharge and the number of days below base turbidity (500 NTU) were the most important variables for influencing periphyton community responses. A significant positive relationship with number of days below base turbidity was found for periphyton biomass in riffle and run habitat (riffle, p = 0.0009; run, p = 0.0575). For biomass in riffle habitat there was also a significant (p = 0.0134) negative relationship with average daily discharge. These variables were important in other periphyton response models but were not as significant. However, the selection of these varialbles and direction of relationships suggest that periphyton communities respond positively to periods of stable or decreasing flows with low turbidity. None of the models selected magnitude of peak flow as an important variable.

In general, data analysis indicated that periphyton community structure was often different when compared between riffle and run habitat. Similar changes throughout each sampling season could be observed in both habitats, but the pattern of changes in metric values was not necessarily similar among years. The most consistent observation among years was the increase in algal growth (density and biovolume) immediately following the period of peak flows associated with snowmelt runoff. After this brief period of growth, densities and biovolume varied throughout the rest of the season. Results suggest that temporal or seasonal influences are not the primary influence on periphyton communities.

The results of this study suggested that riffle habitat usually has the greatest potential for high density and biomass of periphyton. However, in several instances greater densities were reported in run habitat. Periphyton communities in riffles usually have the greatest risk of density reduction due to increases in the frictional shear force associated with higher velocities (Horner and Welch 1981). A reduction in periphyton cell density and biovolume was usually found to occurr after a series of mid-summer storm events. The data suggest that the current velocities in the riffle habitat allow the development of greater densities of periphyton, however, these communities have a higher risk of being reduced by the impact of fine sediment transport (high turbidity, frictional scour and deposition) associated with storm events.

4.2.2 Macroinvertebrates (Clifton Site)

Most would agree that historically (prior to the existence of diversions or dams), the Colorado River supported macroinvertebrate communities (and native fish) that had adapted to the natural flow regimes, sediment regimes, and other physical factors of the environment. These macroinvertebrate communities may have been structurally and functionally different than they are today; unfortunately, quantitative historical data on macroinvertebrate communities in the 15-MR are not available. The intention of this study was not to speculate on comparisons between current and historical macroinvertebrate communities, but rather to identify the physical processes contributing to the structure and function of current macroinvertebrate communities.

Aquatic biota that evolved in snow melt runoff dominated river systems such as the Upper Colorado River have adapted to survive periods of unfavorable conditions, in particular, peak runoff. Many benthic invertebrates have either morphological or behavioral adaptations that allow them to survive through these periods (Hynes 1970). Examples of these adaptations include the emergence of adults or egg deposition during runoff. In addition, some invertebrates are known to have extended periods of time when eggs hatch. Adaptations such as these make a species less vulnerable to adverse conditions that seasonally occur in river systems. These seasonal changes in abundance are seen in the data collected in this study. The data for species diversity and evenness further demonstrate the overall health of secondary (and primary) producers in the 15-MR, which is a result of the current flow regime including the peak flows.

Extreme flows are part of a natural stream ecosystem, and most riverine species have evolved to survive floods and droughts. In physical terms, frequent floods are responsible for most sediment transport, and thus formation and maintenance of in-channel habitats (Richards 2001; Wolman and Miller 1960; Wolman and Gerson 1978; Pitlick and Wilcock 2001). In biological terms, floods are classified as disturbances, especially when they involve mobilization of the streambed (Resh et al. 1988); however, out-of-channel flows are considered to be necessary for maintaining riparian vegetation and floodplain processes (Franz and Bazzaz 1977; Harris et al. 1987; Junk et al. 1989; Hill et al. 1991).

Life histories of most macroinvertebrate species in the 15-MR probably range from several months to one year. The low densities and taxa richness that occurred in samples during the late spring indicate that many of these species have developed behavioral or biological mechanisms (egg stage, terrestrial adult stage, etc.) to avoid harsh aquatic habitat during snowmelt runoff. If post runoff habitat conditions were optimum for macroinvertebrate survival, it is likely that production and standing crop would increase in all habitats and remain high into the winter months.

4.2.2.1 Data Analysis

Trends observed in the macroinvertebrate data were more consistent than those described for periphyton; however, metrics used to analyze macroinvertebrate data, ranged in their ability to describe impact to the communities. Metrics designed to detect pollution (Diversity, Evenness and FBI) exhibited little variation throughout the sampling season of each year. However, it should be noted that slightly lower values for diversity and high values for the FBI during the early sampling occasions of most years may indicate some build up of nutrients during the winter months. EPT and species richness values obtained during this study indicated consistent differences between habitats and some seasonal trends. Production related metrics (density and biomass) clearly indicated changes in macroinvertebrate communities throughout each season and identified differences between habitats.

Results provided by most metrics and most sampling occasions indicated that macroinvertebrate communities are different in riffle and run habitats. Metrics that indicated a preference for riffle habitat by macroinvertebrates included: E.P.T., species richness, density, and biomass. The data shows that the majority of the differences can be attributed to a larger number of taxa and higher densities in riffle habitat. The similarity of pollution-related values between habitats suggests that the difference in communities can mostly be attributed to specific habitat features. The process of sediment deposition has been described as a habitat altering process (Lenat et al. 1981), and therefore, is less likely to be detected by pollution oriented metrics.

Benthic macroinvertebrates, as with periphyton, usually react negatively to inputs of fine sediment (Waters 1995). High turbidity associated with sediment transport increases macroinvertebrate drift (Doeg and Milledge 1991), while sediment deposition has been found to significantly decrease macroinvertebrate abundance and alter community structure and function (Henley et al. 2000). Often the impact on macroinvertebrates is specific to certain taxa or a functional guild. The proportion of collector-filterers in riffle habitat at the Clifton site corresponds closely to trends observed in the production metrics. Kohlhepp and Hellenthal (1992) found that collector-filterers were the most sensitive feeding group to sediment deposition. It is likely that the presence of fine sediments in suspension interferes with their techniques or processes used for food acquisition.

4.2.2.2 Influence of Fine Sediment

The introduction of fine sediments resulting from summer storm events is a major influence on the distribution and production of macroinvertebrates in the 15-MR of the Colorado River. The effects of sediment deposition has been previously discussed, but suspended sediments in high velocity habitats may also impact macroinvertebrates. Culp et al. (1986) found that scouring due to fine sediments (less than 1mm) reduced benthic densities by more than 50% within 24 hours, and significantly changed the macroinvertebrate community structure. The effect of scouring was somewhat species specific, and depended on the specific location in the substrate that was occupied by each taxon. The location of a species and susceptibility to scouring was found to change between day and night suggesting that the duration of exposure may influence the degree of impact. A better understanding of the complex biological processes associated with suspended sediment transport and fine sediment deposition is necessary to predict the extent of impact from disturbance and to evaluate the potential for future impact and recovery.

Habitat quality and quantity were found to be directly associated with flow velocity at all sites in the study area. During times of high flow (> 4800 cfs), velocities were similar in the riffles and runs resulting in physical similarities between these habitats (see Chapter 3). The higher velocity in run habitat during high flows removes fine sediments to expose more cobble size bed material. At times of lower discharge following annual peak flow, the physical attributes of the two habitats, and the effects of fine sediment become quite different. When thunderstorm events occur during low flow periods, most sediment remains in suspension in the higher velocity habitat, while low velocity habitats become areas of sediment deposition. The impact of sediment deposition depends on the frequency and intensity of summer rain events, but can ultimately negate the cleaning effect of annual peak flow. Low velocity associated with low discharge in the run habitat results in an increase in sediment deposition and a decrease in optimal macroinvertebrate habitat. Other researchers have concluded that sediment deposition in low velocity habitats will displace macroinvertebrates resulting in reduction of densities in these habitats (McClelland and Brusven 1980).

General trends determined from analyzing macroinvertebrate data suggest that standing crop and production were greatest in riffle habitat. The only occasion when density and biomass metrics were similar between sites was when high flows had created areas of similar velocity (and consequently similar habitat) at both sites. Flow velocity is responsible for maintaining habitat availability (and consequently diversity) during periods of sedimentation; therefore, macroinvertebrate standing crop in this system is dependent on the velocities associated with each habitat (Table 3-1).

Three metrics (taxa richness, density and biomass) were used in the regression analysis for macroinvertebrates at the Clifton site. The model for each metric used the best assortment of variables to explain the changes in metric values over time. The variable that was consistently significant ($p<0.05$) in all models and each habitat was the number of days below base turbidity (50 NTU) prior to sampling. Increases in taxa richness, density and biomass were always significantly correlated with increases in the number of days below base turbidity. In some instances (taxa richness in run habitat, $p<0.0001$ and biomass in run habitat, $p = 0.0001$) the number of days below base turbidity was the only significant variable that described changes in metric values. The model for density in run habitat also selected average daily discharge as a significant ($p = 0.0345$) variable with a negative relationship.

Average daily discharge was a significant variable with a negative relationship in models for each metric in riffle habitat (richness, $p = 0.0070$; density, $p<0.0001$ and biomass, $p<0.0001$). This was the only significant variable in addition to number of days below base turbidity in the model for biomass in riffle habitat. Percent change in turbidity was a significant ($p = 0.0062$) variable in a negative relationship with density in riffle habitat. Richness in riffle habitat was partially influenced by the number of days above the threshold turbidity level (400 NTU) prior to sampling ($p<0.0001$).

The analysis of physical variables and biological responses suggests that macroinvertebrate standing crop during the summer base flow period is primarily a function of daily discharge and turbidity. Periods of low turbidity (<50 NTU) and stable or declining flows represent the conditions that are most conducive to higher macroinvertebrate standing crops in riffle and run habitat..

4.2.2.3 Peak Flow

The magnitude of annual peak flow may have important long-term implications regarding lower components of the food web in the 15-MR. However, the data collected during this intensive five-year study suggest that the frequent intervals (1 to 3 years) for high (bed mobilizing) peak flows recommended by Osmundson et al. (2002) would have little direct influence on increased or sustained macroinvertebrate populations in the 15-MR. In fact, when annual peak flow was selected as part of a model that best explained changes in a biological metric, the direction of the relationship (although not significant) was negative. Macroinvertebrate data from five sampling seasons in this study indicates that community dynamics in riffle and run habitat are limited by the addition of fine sediments that result from summer thunderstorms following the period of peak flows. Therefore, while the physical processes which produce the framework response are possibly important to the system, the biological responses to transient processes in the summer base flow period are most significant (Figure 4-3).

4.2.2.4 Physical Factors

Physical factors that determine the quality of habitat include sedimentation, turbidity and flow velocity. Factors that could account for the differences in macroinvertebrate community structure and function between habitats include; habitat availability, food availability, and impacts from fine sediment. It is likely that these variables work together with velocity to determine the physical processes that are responsible for distributions of aquatic macroinvertebrates in the 15-MR.

4.2.3 Expanded Study Areas

In 2001, synoptic study sites were added in order to collect representative biological data from other reaches of the Colorado River drainage (one site on the Gunnison River was also included). Data collected from this expanded area provided information regarding periphyton and macroinvertebrate community similarities and the range of expected metric values in a larger area of habitat in the Upper Colorado River, Colorado.

4.2.3.1 Periphyton

Results of periphyton analysis from the synoptic sites exhibited considerable variability on most sampling occasions. The expected variability associated with periphyton sampling, combined with the lack of previous research and analysis tools in the current literature make it difficult to speculate on spatial trends given the low number of sampling events during this study. The data do, however, suggest that periphyton communities are not abundant during the period associated with peak flows. Low densities during peak flow are an expected result of increased flow velocities combined with sediment mobilization and scouring. On other sampling occasions at low flows, this trophic level was well represented at each site in the study area. No other consistent trends were observed.

4.2.3.2 Macroinvertebrates

Macroinvertebrate data indicated several trends when observing results from sites beginning at the upper end of the 15-MR and moving downstream. Diversity and evenness declined slightly in the 18-MR while FBI values increased. This suggests that there may be some influence from pollutants and/or nutrients entering the system in the proximity of the City of Grand Junction. The production metrics (those most effective at detecting impact from sedimentation) indicated clear differences between habitats. The fact that large differences between habitat types were indicated by production metrics and not pollution-related metrics suggests that much of the difference between habitats can be attributed to the deposition of fine sediments in areas of low velocity. This reaffirms the previous discussion regarding data collected over a period of three years at the Clifton site.

4.2.3.3 Validation/Use of Data

A comparison of metric values among sites may be slightly biased due to the influence of toxicants at some locations, but generally indicates the potential for high macroinvertebrate production in riffle habitat at each site in the study area. The data suggest that during 2001 production was greatest in October during fall base flow (given the months that were sampled), and the spatial trend suggests that standing crop increases downstream to a location near Corn Lake and then decreases farther downstream. Additional sampling at these sites would be needed to determine the cause and significance of minor trends that are probably associated with pollutants.

4.2.4 Fish

The small-bodied fish species captured during sampling are consumers of benthic macroinvertebrates and periphyton in the main channel (Koster 1957, Mendelson 1975, Carothers and Minckley 1981, Greger and Deacon 1988, Osmundson 1999, Brooks et al. 2000). These species are also important prey items for Colorado pikeminnow and adult roundtail chub. Osmundson (1999) found that small-bodied fish accounted for over 50% of the identifiable diet of 400-550 mm Colorado pikeminnow. Crayfish may be an unrecognized prey item for certain life stages of native fish within the Colorado River. An adult roundtail chub captured by electrofishing in the 15-MR during 2000, regurgitated an approximately 50 mm crayfish (D. Rees, observation). If utilized, the biomass of crayfish in the Colorado River has the potential to be an important food source. Further research is needed to determine the extent which native fish utilize this prey item as well as to determine a more accurate representation of crayfish abundance within the 15-MR. The hypothesis presented by Osmundson (1999), that carrying capacity of the Colorado pikeminnow within the Colorado River could be increased by enhancing primary and secondary productivity in run habitat, must also be evaluated by using biomass data for the small-bodied fish community. Population estimates for small bodied fish are not routinely collected in the Upper Colorado River Basin.

The density of small-bodied fish in riffles was 3.28 individuals per meter^2 (N=3) in the Colorado River. Run density was 1.30 individuals per meter^2 (N=3) in the Colorado River. Based upon the small set of data, the density of small-bodied fishes in the Colorado River is significantly higher than in a similar reach of the San Juan River in New Mexico (Miller Ecological unpublished data). Numerous factors can influence the densities of these small-bodied fishes within upper basin rivers. Ecosystem level factors such as precipitation, spring peak flow, base flow, storm events, water quality and water temperature can determine the densities of the small-bodied fish community.

4.2.5 Bioenergetics

A highly debated question posed throughout the upper basin is how to determine an accurate, practical carrying capacity for Colorado pikeminnow. Development of Colorado pikeminnow carrying capacity within the 15-MR in part requires a determination of available prey resources as well as information on the amount of prey required to sustain the population. Developing a species specific bioenergetics model to determine consumption rates requires a multitude of data of which most, or all, are lacking for Colorado pikeminnow. Therefore, we approximated a bioenergetics-based Colorado pikeminnow consumption estimate using muskellunge (*Esox masquinongy*) as a surrogate species for Colorado pikeminnow. In subadult/adult sizes, both species assume similar trophic positioning and exhibit similar thermal tolerances. An estimate of the yearly consumption of an individual growing from 632 to 644 millimeters (weight: 2.17 kg to 2.31 kg, similar to the size used by Osmundson (1999)) was determined using Fish Bioenergetics v. 3.0 modeling software (Hanson et al. 1997). The model calculations indicated that a total of 4893 grams of prey were required to grow an individual from 632 to 644 millimeters. Osmundson (1999) developed a carrying capacity of 3-5 adults per kilometer based upon an observed reduction in body condition as well as the principle of habitat capacity. Combining the carrying capacity from Osmundson (1999) with our bioenergetics calculations provides an approximation of the percent of prey biomass consumed by 3-5 adults per kilometer. Using the value of 121 kg/km (based upon boat electroshocking data from Anderson and Irving (1998) presented by Osmundson (1999) and using the same assumptions of Osmundson (1999), 3-5 adults per kilometer would consume 12-20 percent of the available prey. Common electrofishing techniques can demonstrate a bias toward capture of large fish, precluding younger or smaller individuals (Sullivan 1956, Reynolds and Simpson 1978). The data from Anderson and Irving (1998) is from boat electroshocking and most likely has sampling gear bias toward larger sized individuals. Although the Anderson and Irving (1998) data are for individuals less than 300 mm in total length, we assume that individuals below 150 mm are poorly represented and thus added our population data for individuals less than 150 mm to estimate the overall prey population available to Colorado pikeminnow. The total prey biomass (individuals < 300 mm) is approximately 225 kilogram/kilometer. A Colorado pikeminnow adult density of 3-5 fish per kilometer would consume roughly 6-11 percent of the available prey.

4.3 Process-Response Methodology

Relations between flow, habitat, and a widespread range of organisms (periphyton, macrophytes and benthic invertebrates) that use the bed material of rivers as habitat are not well understood (Biggs et al. 2001). Disturbances within the system can have a major impact on in-channel standing crop at any given time, and it is probable that the frequency and duration of disturbance events strongly influences the biotic assemblages. In general, the highest biomass occurs where flood frequency is low and nutrient supply is high (Biggs 2000). The nature of the disturbances in a gravel-cobble bed river is variable, and may or may not, be associated with floods. Increases in local near bed velocity or shear stress, as a result of increased discharge in the river, can lead to increases in drag on benthic communities that can lead to detachment and downstream transport of organisms. Filamentous algae, that are present within the 15-MR, are particularly susceptible to velocity-related dislodgement (Biggs and Thomsen 1995). Substantial mobilization of the bed sediment during a flood causes major displacement or mortality in benthic communities (Power 2001). Abrasion of the benthic communities as a result of increased suspended-sediment concentrations can also lead to adverse effects (Newcombe and MacDonald 1991). Finally, deposition of suspended sediment being transported by the flows, without mobilization of the underlying gravels and cobbles, causes benthic smothering (Henley et al. 2000). Although empirical relations between flows, habitat and the benthic community dynamics can be developed, validation of the relations between habitat use and flow requirements ultimately requires that the basis for the relations be established with some form of physical process-biological response model, or methodology (Hill et al. 1991; Tyus 1992; Harvey et al. 1993).

Much of the work that has been reported to date relating fine sediment deposition to biological effects has been focused on gravel-cobble bed streams where salmonids spawn. The fine sediments studied are composed of fine gravels and sands (between about 1 and 10 mm in diameter) that have infiltrated into the interstices between the framework particles (about 50 to 100 mm in diameter) that form the bed of the channel (e.g., Kondolf and Wilcock 1996; Milhous 1998). In the context of salmonid requirements for successful spawning, a number of previous studies have shown that these fine sediments (sands and fine gravels) cannot be winnowed or flushed from the necessary depths within the bed material without mobilization of the framework gravels that make up the bed of the river (Beschta and Jackson 1979; Berry 1985; Diplas 1994; Kondolf and Wilcock 1996; Milhous 1998). Using this concept, Pitlick et al. (1999) concluded such conditions are desirable in the Colorado River system and estimated that incipient-motion conditions for the gravel-and-cobble sediments that comprise the bed material of the Colorado River within the 15-MR occurs at about half the bankfull discharge (about 10,500 cfs) and that general bed mobilization of the bed material required to flush the finer sediments considered in the salmonid spawning model takes place at a discharge that corresponds with the bankfull discharge (about 22,000 cfs). Based on this concept which requires mobilization of the bed material by flood flows to create salmonid spawning habitat, it has been postulated that removal of fines by increasing the magnitude of peak flows within the 15-MR (or other reaches) will result in more areas of suitable substrate for increased productivity, and thus, an increase in the overall carrying capacity for listed native fish species in the Upper Colorado River (Lamarra 1999; Osmundson and Scheer 1998; Osmundson et al. 2002).

4.3.1 General Conceptual Model

Based on the observations in the 15-MR since 1999, it is apparent that the salmonid model of fine sediment infiltration into framework gravels, and subsequent mobilization of the gravels and cobbles to eliminate the biological impairment, is not a complete model for the UCR. Although bed mobilization and sediment flushing does occur (i.e. framework response), a more complete model includes a recognition that the biological productivity of the river during low-flow periods that occur for about three quarters of the year, is dependant on the presence, or absence, of a temporally variable supply of fine sediment (primarily fine sand, silt and clay) (i.e., transient response). This fine sediment (mud) is not present in the stream where the salmonid model is appropriate and here is generated by runoff from precipitation events, before or after the snowmelt-runoff season, in the lower elevation portions of the basin that are underlain by highly erodible sedimentary rocks (Spahr et al. 2000). The suspended sediments delivered to the Colorado River in the post-runoff period, when the flows in the river are generally less than 1,500 cfs in the 15-MR, are deposited in locations where local hydraulic conditions, defined either by mean column velocity (Table 3-1) or shear stress (Table 3-2), permit the sediments to be deposited. Re-entrainment of the deposited sediments occurs at a range of flows where the local velocities (Table 3-1) or shear stresses (Table 3-2) exceed the thresholds for deposition of the fine sediments, but do not involve mobilization of the underlying gravels and cobbles that make up the bed of the river. Hydrodynamic modeling permits the spatial distribution of both velocities and shear stresses within a site to be established over a wide range of flows, and these can be related to the potential for sediment deposition, and therefore, biological productivity, through the identified thresholds. However, prediction of the biological productivity at a site in any given year depends on the occurrence of fine sediment-producing runoff events, and is therefore, stochastic.

4.3.2 Process-Response Model Application to 15-MR

The results of the field observations and analyses at the Clifton and Corn Lake sites in the 15-MR, allow for the development of a quantitative process-response model that relates the hydraulic and sediment dynamics to the presence or absence of biological productivity-limiting fine sediment (mud) deposits (Figure 4-3).

The benthic biota respond to the changes in the physical processes (Figure 4-9). Density and biomass of benthic biota are reduced after bed mobilization and fine sediment deposition. The density response after peak flow may be a behavioral adaptation to the snowmelt runoff flow regime, while the density reduction after fine sediment deposition during base flow is more likely the result of mortality and displacement due to a stochastic disturbance.

Biological productivity, as a function of discharge, is indicated by the distribution of the mud classes in Figure 4-4. In general, higher productivity occurs in areas with higher velocity.

These higher velocity areas have cleaner substrates and therefore more habitat available for benthic organisms than the lower velocity, fine sediment covered substrates.

The bed and bar margins where fine sediments are likely to be deposited, are composed of gravel and cobble sized sediments that range in size from about 20 mm to 256 mm. At the Clifton site, the median size (D_{50}) of the surface bed material in the riffles is on the order of 80 mm, and the D_{84} is about 105 mm (Figure 3-11). The D_{50} of the surface sediments in the run is about 85 mm and the D_{84} is about 108 mm (Figure 3-10). The interactions between the gravel and cobbles and the snowmelt runoff flows constitute the framework responses (Figure 4-3). Threshold conditions for mobilization of the coarse sediments in the riffles occur at a discharge of about 4,800 cfs, and in the runs at discharges of about 13,000 cfs. Total mobilization of the bed materials throughout the site occurs at discharges in excess of 20,000 cfs. The mud that is deposited on the surface gravels and cobbles (Figure 3-13) is composed of fine sands, silts and clays. Between 97 and 100 percent of the samples are sand sized and finer (Figure 3-14), and silts and clays make up between 40 and 60 percent of the sample (Figure 3- 30).

The supply of the fine sediments to the 15-MR is temporally variable. In general, the Cameo gage suspended sediment records (Figure 3-28) show that the higher concentrations occur at the higher discharges. However, the fixed interval gage record does not fully represent the post-runoff thunderstorm related events (Figure 3-29). Comparison of the Cameo gage data with the Clifton data shows that the highest concentrations occur during the post-runoff thunderstorm-generated events, or when there is a high supply of sediment within the channel at the onset of the snowmelt runoff, such as occurred in WY 2002. While there may be a weak relationship between turbidity and suspended sediment concentration (Figure 3-18), turbidity measurements provide a semi-quantitative means of identifying those events where summer thunderstorm runoff delivers fine sediment to the 15-MR (Figure 3-17). In WY 2001, there were about 8 fine sediment delivering events in the post-runoff period, while in WY 2000 there were very few events. Similarly, there were few post-runoff events in WY2002, and a higher number in WY2003.

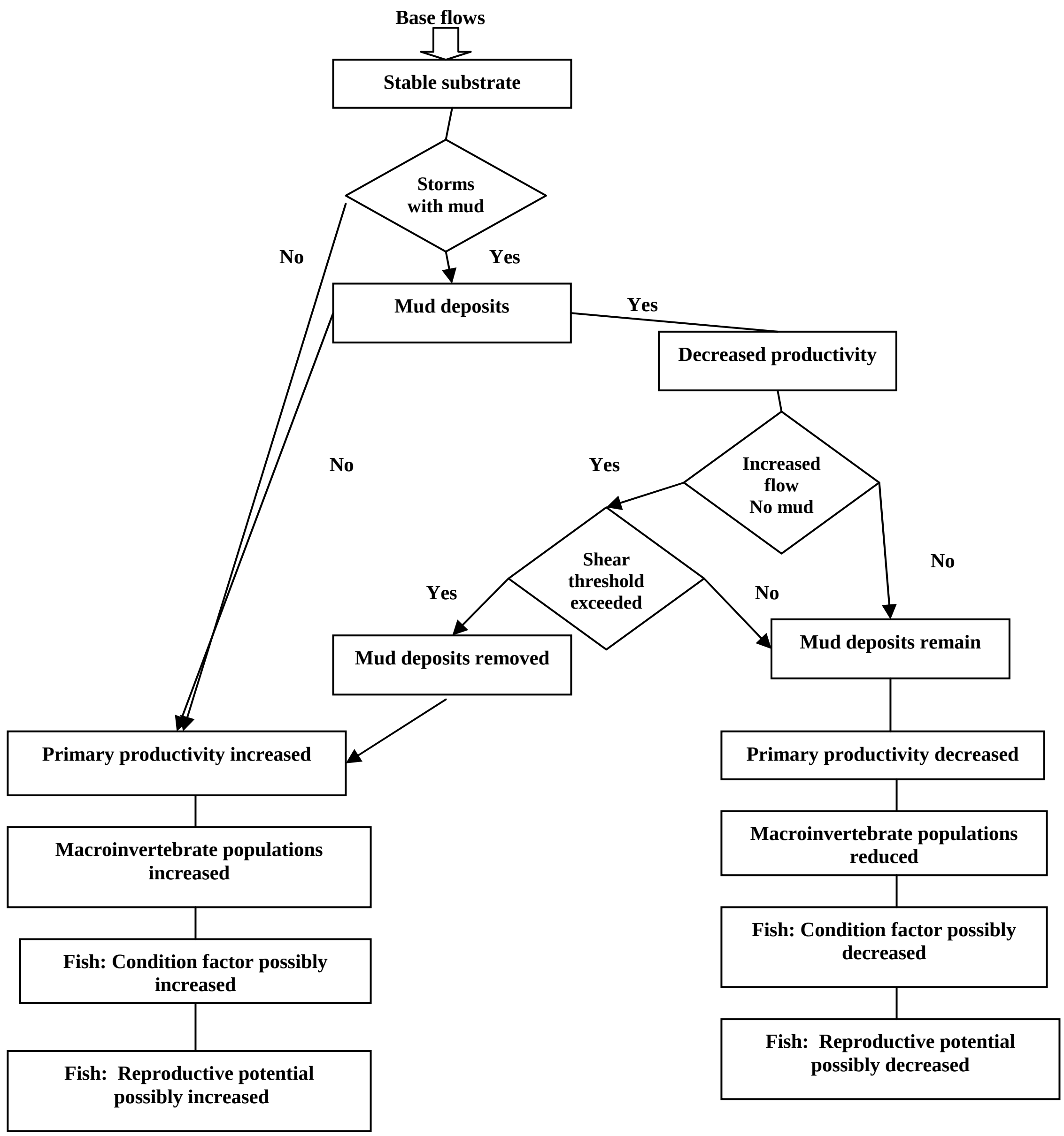


Figure 4-8. Biological response to physical processes in riffle and run habitat in the 15 MR.

Biological productivity is substantially different for post-runoff conditions with and without summer rainstorm events. During the summer baseflows of 2000, rainstorms did not occur until August and flows were clear and stable during July. The difference in productivity from these two different conditions is shown in Figure 4-5. July productivity values appear to show that both velocity and water clarity are factors that affect benthic organisms. The samples taken in higher velocity water (i.e. riffle habitat (Figure 4-10)) have substantially higher density than the samples collected in lower velocity water (i.e. run habitat) even under clear water conditions. The riffle habitats had 6.9 times higher density and 8.5 times higher biomass than run habitats on average.

The August samples taken just days after a summer thunderstorm and influx of fine sediment shows little difference in density as a function of velocity. Both the lower and higher velocity samples have relatively low density values when compared to the July conditions, which indicates that clean substrate and therefore clean habitat is the primary control for productivity with velocity being secondary.

Analysis of the mean daily flow record for the Palisade gage (Figure 3-8) shows that the normal post-runoff range of flows in the 15-MR (800 cfs-1,500 cfs) are equaled or exceeded between about 70 and 90 percent of the time, and therefore, it is within this range of flows where the transient responses are likely to have the most effect on the biological productivity. Mapping of the various mud classes (Table 2-1) at the Clifton site at a discharge of about 1,000 cfs (Figure 3-23) following a number of thunderstorm-generated events, and the attendant quantification of velocities (Figure 3-24) and shear stresses (Figure 3-25) within each of the mapping units provides a basis for defining threshold conditions for mud deposition and re-entrainment. Velocity-based thresholds for the 5 sub-aqueous mud classes developed from the Clifton and Corn Lake sites are very similar (Tables 3-2, 3-4). If fine sediment is being transported by the river, mud deposition will occur when mean velocities are less than 2.5 fps (classes 2, 3, 4). Above a mean velocity of 2.5 fps (classes 5 and 6), mud deposition substantially decreases. A shear stress threshold value of 0.03 lb/ft^2 also defines the upper limit of significant mud deposition (Table 3-2). Comparison of the mapped fine sediment deposition in the Clifton reach at a discharge of about 1,000 cfs (Figure 3-23) and the predicted areas of deposition based on the

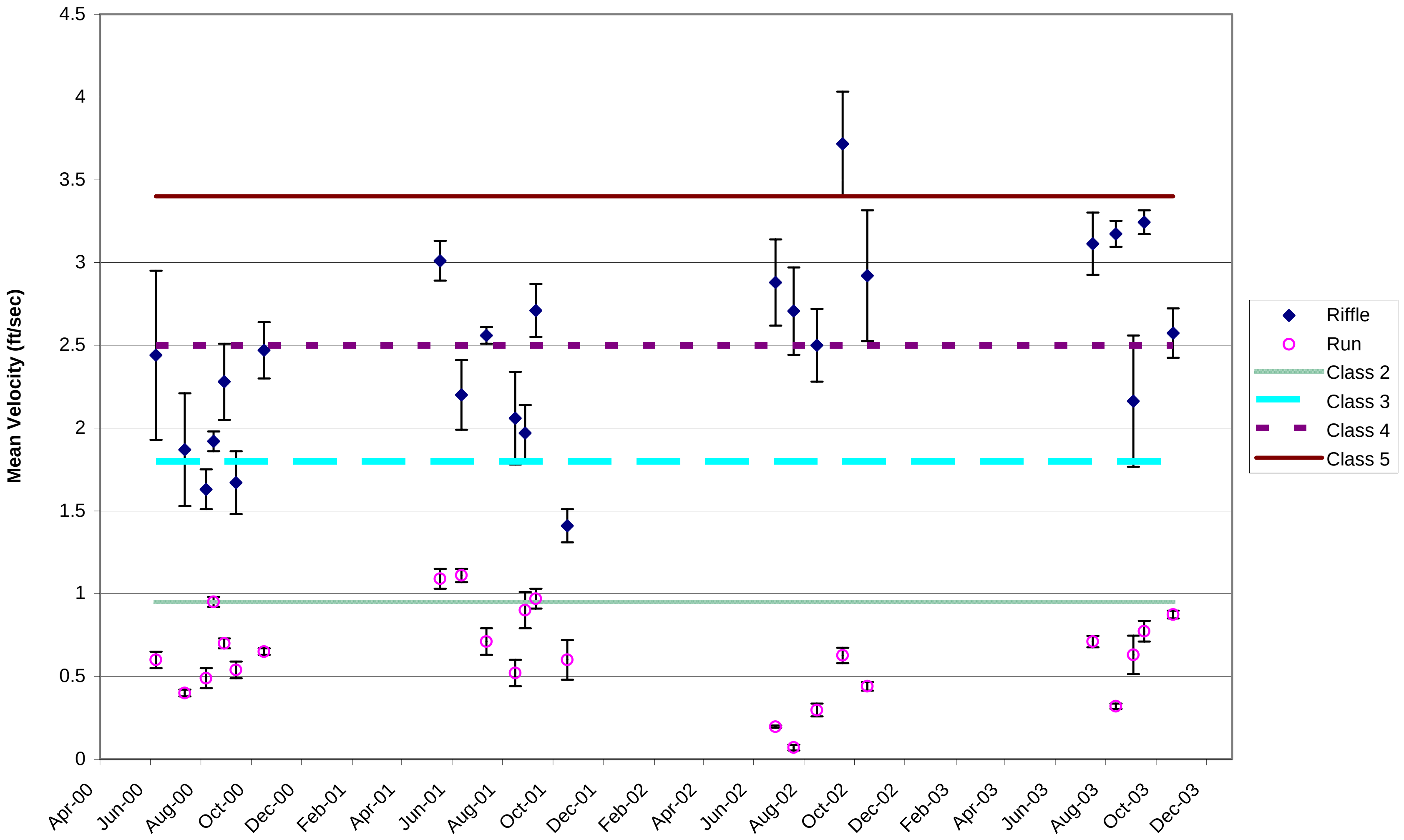


Figure 4-10. Mean point velocities (± 1 standard error) for biological sampling at the Clifton site with illustrated thresholds for mud classes.

computed shear stress (Figure 3-40) shows that the 2-D model predicts mud deposition reasonably well, and is, therefore, a reasonable basis for prediction of mud deposition for other flows. Knowing the spatial distribution of the mud deposits over a range of flows less than about 4,800 cfs, when bed material mobilization occurs in the riffles, provides a means of quantifying the biological impacts of the mud deposits throughout the site.

Increased productivity was observed every year during post runoff base flows prior to the onset of summer thunderstorms. The productivity continued to increase as long as the flows were stable and the substrate remained free of fine sediment. When fine sediment was deposited after summer thunderstorms, primary and secondary productivity decreased. The density and biomass usually increased later in the fall, however, the amount of increase appears to be related to the number of summer thunderstorms, amount of fine sediment introduced, and flow.

The bar graphs in Figure 4-4 show the surface area (ft^2) of the Clifton site by mud class for the range of discharges between 800 and 4,800 cfs. The total area of the site increases from 12.9 ac at 800 cfs to 15.7 ac at 4,800 cfs. At 800 cfs, about 35 percent of the site is essentially mud free (shear stress > 0.03 lb/ft^2), and the majority of the mud-free area is located in the riffles and the middle of the runs (Figure 3-39). At discharges of 1,100 and 1,400 cfs about 47 to 54 percent of the site is essentially mud free, but the mid-channel bar, channel margins and the margins of the lower run have the potential to contain significant amounts of mud (Figures 3-40 and 3-41) because the shear stress is less than 0.03 lb/ft^2. At a discharge of 2,000 cfs (Figure 3-42) about 67 percent of the site is essentially mud free, with most of the potential for mud deposition being on the margins of the channel and mid-channel bar. About 85 percent of the site is essentially mud free at a discharge of 4,800 cfs (Figure 3-43).

The information in Figure 4-4 can be used to manage the depositional areas for fine sediment after summer thunderstorm events. The objective would be to raise velocity slightly, sweep the deposited material off the surface of the substrate and provide an increased area of cleaner habitat. The amount of discharge increase would be small to still maintain a summer base flow level but enough of an increase to result in higher productivity over the summer and into fall. A large flow spike during baseflow could possibly be detrimental to the invertebrates and periphyton on the substrate even though it would remove the fine sediments.

The 2-D modeling shows that small changes in discharge can result in substantial increases in areas that exceed the shear stress thresholds for fine sediment scour. There are 12 percent and 20 percent increases in mud free area when discharge increases from 800 cfs to 1100 cfs and 1400 cfs, respectively. The potential productivity of these mud-free areas are similar to the conditions represented by the riffle samples collected over the course of this study.

The current peak flow regime (1950-2001) including the lower frequency of high discharge events provides the necessary physical disturbance regime for the 15 MR to reset the framework materials and maintain the current channel morphology (Pitlick et al., 1999). The primary and secondary productivity levels are more a function of summer base flow and fine sediment input than peak flow magnitude. Since the riffle habitat has much higher biomass and density than run habitat, small changes in area that exceed the shear stress threshold for fine sediment should result in large changes in overall productivity. These areas of suitable sediment free conditions occur not only in the riffles but also in the center of the run habitats. Therefore, summers with slightly higher base flows during periods with frequent thunderstorms should result in higher productivity levels in the fall when compared to summers of frequent thunderstorms and lower base flows.

5 CONCLUSIONS

While the current morphology of the Colorado River within the 15-MR may be in equilibrium with the post-1950's peak flow regime and sediment supply, the question of the adequacy of the current peak flow regime for fine sediment flushing and biological productivity (Osmundson et al 2002) cannot be addressed by a generalized study of sediment mobilization. Pitlick et al. (1999) identified discharges for incipient mobilization of the bed material (10,000 cfs) and for general mobilization of the bed material (22,000 cfs), but as pointed out by Downes et al (1997) flow-sediment-habitat relations occur at micro-and meso-scales levels that are not represented by macro-scale analyses.

The primary goals of the physical process portion of this investigation were to address specific aspects of the sediment dynamics of the 15-MR at meso- and micro-scale levels so that they could be directly related to the quality of the habitat in the riffles and runs, and hence biological productivity.

The specific areas of investigation and the findings of this study are addressed as follows:

- Factors that control the supply of fine sediment to the 15-MR and the timing of the sediment supply.

  The fine sediment is derived from the lower elevations of the UCR basin that are underlain by highly erodible sedimentary rocks. The fine sediment, that is composed mainly of fine sands, silts and clays, is delivered to the Colorado River during baseflow periods primarily by summer thunderstorms that do not increase the discharge of the Colorado River greatly, but do increase the suspended sediment concentrations. Even though reported suspended sediment concentrations have not changed appreciably in the last 50 years, they are lower currently than they were prior to the 1940's. Because of the geologic and climatic settings, the suspended sediment loads in the 15-MR have always been high.

- The hydrodynamic conditions within the reach that permit mud deposition and the resulting spatial distribution of the mud within the reach.

  Velocity and shear stress thresholds for mud deposition and erosion were identified from field measurements at the Clifton and Corn Lake sites. At locations where velocity and shear stress are higher than 2.5 fps and 0.03 lb/ft^2, respectively mud is not deposited in appreciable quantities. The good correlation of the mapped boundaries of the mud mapping units with the predicted boundaries from 2-D modeling at Clifton enables the spatial distribution of the mud at the site to be predicted with reasonable confidence over a wide range of flows.

- The hydrodynamic conditions within the reach that permit general mobilization of the gravel and cobble that constitute the bed sediment in the riffles and the runs.

  Incipient motion calculations based on output from the 2-D model of the Clifton site identified critical discharges for the riffles and the runs. The critical discharge in the riffles is about 4,800 cfs, and in the run it is between 13,000 and 15,000 cfs. General mobilization of the bed material throughout the site occurs at flows in excess of 20,000 cfs.

- The range of flows required to deposit and remove fine sediment from the bed of the channel.

  Provided that fine sediment producing events have occurred in the upstream tributaries, mud is deposited at various locations within the Clifton site where the velocity is less than 2.5 ft/s or shear stress is less than 0.03 lb/ft^2. Mud is re-entrained from these locations when the identified velocity or shear stress thresholds are exceeded. The results of the 2-D modeling of the Clifton site indicate that at a flow of 800 cfs (equaled or exceeded 92 percent of the time), about 35 percent of the site is relatively mud-free. At flows of 1,100 cfs and 1,400 cfs (equaled or exceeded about 80 percent of the time), about 47 to 54 percent of the site is relatively mud-free. At a flow of 2,000 cfs (equaled or exceeded 45 percent of the time), about 67 percent of the site is mud-free. About 85 percent of the site is mud-free at a flow of 4,800 cfs (equaled or exceeded 16 percent of the time).

- Whether it is necessary to mobilize the underlying coarse-grained bed material for flushing of accumulated fine sediment.

  Flushing of fine sediments from the gravels and cobbles that make up the bed of the river in the riffles and runs at the Clifton site occurs at flows in excess of 4,800 cfs and 13-15,000 cfs in the riffles and runs, respectively, when the critical discharge is exceeded, and this is described by the framework response of the process-response model. However, the results of the 2-D modeling show that the surficial fine sediments can be re-mobilized and flushed by less than critical flows for the underlying bed material throughout the Clifton site, and this is described by the transient response portion of the process-response model.

Previous research on the 15-MR of the Colorado River (Lamarra 1999) supports our preliminary conclusions that primary and secondary production occur at higher rates in riffle habitats as opposed to run habitat. Lamarra (1999) and Osmundson et al. (2002) also contend that higher peak flows during the runoff period may result in higher primary and secondary productivity thereby indirectly increasing fish condition and carrying capacity. The results of this study suggest that a number of variables (including flow regime) are responsible for determining standing crop and productivity at lower levels in the food chain. High flow velocities associated with riffle habitat contributed to a greater biomass and higher densities of periphyton and macroinvertebrates during periods of low stable flow. The increase in the standing crop in riffle and run habitat coincided with periods of flow stability and decreases in turbidity. Based on evidence provided by this research it seems that a variety of physical processes (discharge, turbidity, frequency and intensity of storm events, deposition of sediments, specific runoff characteristics, scouring by sediments, etc.) are responsible for influencing periphyton and macroinvertebrate standing crop in the 15-MR of the Colorado River.

Results of the biological portion of this study indicate that lower trophic levels are present and exhibit a range of structure and function that would be expected given the constraints provided by physical processes. The data suggest that the potential for production is high during periods of low turbidity and stable flow. This potential was observed during a period of relatively low, clear, stable flows following peak flows during the year 2000 and low, stable flows resulting from drought conditions in 2002.

Much of the results and discussion provided by this study comply with the biological objectives stated in the first section of this report. Several ecological processes pertaining to interactions between physical variables and lower trophic levels were identified and explained. Peak flow was not identified as a major influence on primary and secondary standing crop or productivity; however, it may still be an important long-term (>3 years) variable. The specific objectives of the study are listed as questions below, with responses based on the findings of this study:

- Are primary and secondary productivity and standing crop dependant on magnitude of peak flow?

  Magnitude of annual peak flow had little or no measurable effect on the variation observed in periphyton and macroinvertebrate communities in the 15-MR during this study.

- Is there a relationship between turbidity produced by summer thunderstorms and standing crop of macroinvertebrates and periphyton?

  There were significant ($p<0.10$) relationships between changes in mean daily turbidity and all aspects of periphyton and macroinvertebrate community structure that were statistically analyzed.

- Is there a difference in primary and secondary production between two major habitat types (run and riffle) in the 15-Mile-Reach of the Colorado River.

Mean periphyton and macroinvertebrate standing crop was much greater in habitats with higher flow velocities.

- Are there seasonal or annual patterns for standing crop of lower components of the food chain in the 15-Mile-Reach of the Colorado River.

  The data indicate that there are seasonal patterns associated with periphyton and macroinvertebrate communities; however, these patterns were usually not realized because the effects of summer thunderstorms were a more dominant force on these communities.

- Are there spatial differences in primary and secondary production in reaches of the lower Colorado River drainage in Colorado?

  The results of one year (2001) of sampling in an expanded range of locations suggested that there are some consistent similarities and differences in different reaches of the 15-MR and 18-MR of the Colorado River.

- Is there a relationship between primary and secondary productivity and listed native fish population carrying capacity?

  The results of this study have provided useful information regarding specific components of this relationship; however additional research is needed.

Aquatic communities in the 15-MR are dynamic and dependent on a variety of physical and biological variables. Differences in structure and function of the benthic communities depend on the specific attributes of available habitat types. Evidence from five years of seasonal sampling suggests that periphyton and macroinvertebrate communities exhibit some predictable seasonal change, have specific habitat preferences or requirements, and are also dependant on physical processes. These results suggest that much of the biological variability can be attributed to physical processes that occur after the annual peak flow associated with snowmelt runoff. These physical processes include; turbidity, velocity and deposition of fine sediments that result from summer thunderstorms.

5.1 Recommendations

To-date most of the analyses of sediment mobilization and transport within the 15-MR have been conducted at a reach-scale, and no analyses have been conducted at the scale of individual habitat units. Meso- and micro-scale analyses are required to develop a realistic understanding of the flow requirements and the relationship between flow regime and the formation and maintenance of in-channel habitat units such as pools, riffles and runs. Only at meso-and micro-scale levels can a process-response method be developed that can then be used to evaluate the role of a range of flows in forming and maintaining habitat.

Use of the approach presented in this study in the 18-Mile Reach of the Colorado River and the lower Gunnison River will further the understanding of the ecosystem which supports the listed and other native species. The physical process - biological response model, and data collected to develop and drive it, will greatly enhance the evaluation of flow and habitat related recovery actions, bi-annual review and modification of the Recovery Action Plan, the review and revision of flow recommendations required by the 5 year review of the Recovery Goals, and operations of the Aspinall Unit and other storage projects to achieve recovery. By utilizing several ecosystem components, consideration of the benefits of flow management can more quickly be ascertained and incorporated into adaptive management strategies.

It is recommended that this approach be implemented to demonstrate the utility of the PRM in evaluating the response of the ecosystem of the 15 -Mile Reach, the 18-Mile Reach and the lower Gunnison River to flows, sediment and flow management efforts. This work is directly related to recovery of the listed species as:

- the use of the physical process - biological response methodology (PRM) will provide a bottom to top understanding of the ecology of the Colorado and Gunnison rivers;

- observation of the changes in the ecology of the Colorado and Gunnison rivers using the PRM has the potential to provide a nearly real time direct measure of the response of the ecosystem to the available physical conditions and its ability to support native fish populations necessary for recovery; and

- use of the PRM to guide management actions will enable prediction and evaluation of the response of the ecology of the Colorado and Gunnison rivers to available flow, flow enhancement measures and local sediment inputs.

6 LITERATURE CITED

Allan, J. D. 1995. Stream ecology: structure and function of running waters. Chapman and Hall, London, England.

Anderson, R. M., and D. I. Irving. 1998. Instream flow recommendations for the Colorado River from Palisade to Rifle. Draft Report. Colorado Division of Wildlife, Fort Collins, Colorado.

Andrews, E. D. 1984. Bed material entrainment and hydraulic geometry of gravel-bed rivers in Colorado. Geol. Soc. America Bulletin 95:371-378.

Balling, R. C., and Wells, S. G. 1990. Historical rainfall patterns and arroyo activity within the Zuni River drainage basin, New Mexico. Annals of the Assn. American Geographers, 80(4)603-617.

Berry, C. A. 1985. Bedload transport processes in a cobble-bed channel. Master's Thesis, Colorado State University, Dept. of Earth Resources, Fort Collins, Colorado.

Beschta, R. L., and W. L. Jackson. 1979. The intrusion of fine sediments into a stable gravel bed. Journal of the Fisheries Research Board of Canada 36(3)204-210.

Biggs, B. J. F., and H. A. Thomsen. 1995. Disturbance in stream periphyton by perturbations in shear stress: time to structural failure and differences in community resistance. Journal of Phycology 31:233-241.

Biggs, B. J. F., C. Kilroy, and R. L. Lowe. 1998. Periphyton development in three valley segments of a New Zealand grassland river: test of a habitat matrix conceptual model within a catchment. Archiv fur Hydrobiologie 143:147-177.

Biggs, B. J. F. 2000. Eutrophication of streams and rivers: dissolved nutrient-chlorophyll relationships for benthic algae. Journal of the North American Benthological Society 19:17-31.

Biggs, B. J. F, M. J. Duncan, A. M. Suren, and J. R. Holomuzki. 2001. The importance of bed sediment stability to benthic ecosystems of streams. Gravel Bed Rivers V, New Zealand Hydrological Society, Caxton Press, Christchurch, New Zealand.

Brooks, J. E., M. J. Buntjer, and J. R. Smith. 2000. Non-native species interactions: management implications to aid in recovery of the Colorado pikeminnow (*Ptychocheilus lucius*) and razorback sucker (*Xyrauchen texanus*) in the San Juan River, CO-NM-UT. Final Report. U.S. Fish and Wildlife Service, Albuquerque, New Mexico.

Cairns, J. Jr. 1990. The genesis of biomonitoring in aquatic ecosystems. The Environmental Professional 12:169-176.

Cairns, J. Jr., and J. R. Pratt. 1992. A history of biological monitoring using benthic macroinvertebrates. Pages 10-27 *in* D. M. Rosenberg and V. H. Resh, editors. Freshwater Biomonitoring and Benthic Macroinvertebrates. Chapman and Hall, New York.

Carothers, S. W., and C.O. Minckley. 1981. A survey of the fishes, aquatic macroinvertebrates, and aquatic plants of the Colorado River and selected tributaries from Lee's Ferry to Separation Rapids. Final report prepared for Water and Power Resources Service, Boulder City, Nevada. Contract no. 7-07-30-X0026.

Chow, V. T. 1958. Handbook of Applied Hydrology. McGraw–Hill Book Company.

Ciborowski, J. J. H., P. J. Pointing, L. D. Corkum. 1977. The effect of current velocity and sediment on the drift of the mayfly *Ephemerella subvaria* Mcdunnough. Freshwater Biology 7:567-572.

Cooke, R. U., and R. W. Reeves. 1976. Arroyos and environmental change in the American Southwest. Oxford Research Studies in Geography, Clarendon Press, Oxford, England.

Cordone, A. J., and D. W. Kelley. 1961. The influences of inorganic sediment on the aquatic life of streams. California Fish and Game 47:189-228.

Culp, J. M., F. J. Wrona, and R. W. Davies. 1986. Response of stream benthos and drift to fine sediment deposition versus transport. Canadian Journal of Zoology 64:1345-1351.

Davies-Colley, R. J., and M. E. Close. 1990. Water colour and clarity of New Zealand rivers under baseflow conditions. New Zealand Journal of Marine and Freshwater Research 24:357-365.

Davies-Colley, R. J., W. N. Vant, and D. G. Smith. 1993. Colour and clarity of natural waters. Ellis Horwood, New York, New York.

Davies-Colley, R. J., and D. G. Smith. 2001. Turbidity, suspended sediment, and water clarity: a review. Journal of the American Water Resources Association 37(5):1085-1101.

Dendy, F. E., and G. C. Bolton. 1976. Sediment-yield-runoff-drainage area relationships in the United States. J. Soil Water Conservation 31:264-266.

Diplas, P. 1994. Modeling of fine and coarse sediment interaction over an alternate bar. Journal of Hydrology 159:335-351.

Doeg, T. J., and G. A. Milledge. 1991. Effect of experimentally increasing concentrations of suspended sediment on macroinvertebrate drift. Australian Journal of Marine and Freshwater Research 42:519-526.

Downes, B. J., A. Glaister, and P. S. Lake. 1997. Spatial variation in the force required to initiate rock movement in 4 upland streams: implication for estimating disturbance frequencies. Journal of the North American Benthological Society 16:203-220.

Einstein, H. A. 1950. The bed-load function for sediment transportation in open channel flows. U.S. Department of Agriculture, Soil Conservation Service, Washington, D.C. Technical Bulletin No. 1026.

Franz, E. H., and Bazzaz, F. A. 1977. Simulation of vegetation response to modified hydrological regimes: a probabilistic model based on niche differentiation in a floodplain forest. Ecology 58(1):176-183.

Gellis, A., R. Hereford, S. A. Schumm, and B. R. Hayes. 1991. Channel evolution and hydrologic variations in the Colorado River Basin: factors influencing sediment and salt loads. Journal of Hydrology 124:317-344.

Graf, W. H. 1971. Hydraulics of sediment transport. McGraw-Hill Book Company.

Graham, A. A. 1990. Siltation of stone-surface periphyton in rivers by clay-sized particles from low concentrations in suspension. Hydrobiologia 199: 107-115.

Greger, P. D., and J. E. Deacon. 1988. Food partitioning among fishes of the Virgin River. Copeia 1988:314-323.

Hanson, P. C., T. B. Johnson, D. E. Shindler, and J. F. Kitchell. 1997. Bioenergetics model 3.0 for Windows. University of Wisconsin, Sea Grant Institute, Madison, Wisconsin. Technical Report WISCU-T-97-001.

Hadley, R. F. 1974. Sediment yield and land use in southwest Unites States. Int. Assn. Hydro. Pub. 113:96-98.

Hadley, R. F. 1977. Evaluation of land-use and land-treatment practices in the semiarid western United States. Philosophical Transactions Royal Society of London 278:543-554.

Haralamipides, K., J. A. McCorquodale, and B. G. Krishnappan. 2003. Deposition properties of fine sediment. Journal of Hydraulic Engineering 129(3):230-234.

Harris, R. R., Fox, C. A. and Risser, R.. 1987. Impacts of hydroelectric development on riparian vegetation in the Sierra Nevada region, California. Environmental Management 112(4):519-527.

Harvey, M. D., and R. A. Mussetter. 1994. Green River endangered species habitat investigations. Report to the Colorado River Water Conservation District.

Harvey, M. D., R. A. Mussetter, and E. J. Wick. 1993. A physical process-biological response model for spawning habitat formation for the endangered Colorado Squawfish. Rivers 4(2)1-19.

Harvey, M. D., R. A. Mussetter, and R. D. Tenney. 2002 (in review). Use of process-response model to identify Colorado pikeminnow spawning sites in the Colorado River Basin. Water Resources Bulletin.

Henley, W. F., M. A. Patterson, R. J. Neves, and A. D. Lemly. 2000. Effects of sedimentation and turbidity on lotic food webs: a concise review for natural resource managers. Reviews in Fisheries Science 8(2):125-139.

Hildrew, A. G., and C. R. Townsend. 1987. Organization in freshwater benthic communities. Pages 347-371 *in* J. H. R. Gee and P. S. Giller, editors. Organisation of communities past and present. Blackwell Scientific Publications, Oxford, England.

Hill, M. T.,W. S. Platts, and R. L. Beschta. 1991. Ecological and geomorphological concepts for instream and out-of-channel flow requirements. Rivers 2(3):198-210.

Horner, R. R., and E. B. Welch. 1981. Stream periphyton development in relation to current velocity and nutrients. Canadian Journal of Fisheries and Aquatic Sciences 38:449-457.

Horner, R. R., E. B. Welch, M. R. Seeley, and J. M. Jacoby. 1990. Responses of periphyton to changes in current velocity, suspended sediment and phosphorus concentration. Freshwater Biology 24:215-232.

Hynes, H. B. N. 1970. The ecology of running waters. University of Toronto Press, Toronto, Canada.

Iorns, W. V., C. H. Hembree, and G. L. Oakland. 1965. Water resources of the Upper Colorado River Basin-Technical Report. U.S. Geological Survey Professional Paper.

Judy, R. D. Jr., P. N. Seeley, T. M. Murray, S. C. Svirsky, M. R. Whitworth, and L. Ischinger. 1984. 1982 National Fisheries Survey, Volume 1. Technical Report: Iinitial Findings. Report No. FWS/OBS-84/06, Washington, D.C.: U.S. Fish and Wildlife Service.

Junk, W. J., P. B. Bayley, and R. E. Sparks. 1989. The flood pulse concept in river-floodplain systems. Can. Spec. Publ. Fish. Aquatic. Sci. 106:110-127.

Kirk, J. T. O. 1998. Optical water quality-what does it mean and how should we measure it? Journal of the Water Pollution Control Federation 60:194-197.

Kondolf, G. M., and P. R. Wilcock. 1996. The flushing flow problem: defining and evaluating objectives. Water Resour. Res. 32:2589-2599.

Kohlhepp, G. W., and R. A. Hellenthal. 1992. The effects of sediment deposition on insect populations and production in a northern Indiana stream. Pages 73-84 *in* T. P. Simon and W. S. Davis, editors. Environmental indicators: measurement and assessment endpoints. U.S. Environmental Protection Agency, EPA Report 905/R-92/003, Washington, D.C.

Korte, V. L., and D. W. Blinn. 1983. Diatom colonization on artificial substrata in pool and riffle zones studied by light and scanning electron microscopy. Journal of Phycology 19:332-341.

Koster, W. J. 1957. Guide to the fishes of New Mexico. University of New Mexico Press, Albuquerque, New Mexico.

Koster, W. J. 1957. Guide to the fishes of New Mexico. University of New Mexico Press, Albuquerque, New Mexico.

Lamarra, V. A. 1999. Longitudinal variation in the trophic structure of the Upper Colorado River. Final Report. Ecosystems Research Institute, Inc., Logan, Utah.

Langbein, W. B., and S. A. Schumm. 1958. Yield of sediment in relation to mean annual precipitation: Am. Geophys, Union Trans. 39:1076-1084.

Lenat, D. R., D. L. Penrose, and K. W. Eagleson. 1981. Variable effects of sediment addition on stream benthos. Hydrobiologia 79:187-194.

Liebermann, T. D., D. K. Mueller, J. E. Kircher, and A. F. Choquette. 1989. Characteristics and trends of streamflow and dissolved solids in the upper Colorado River basin, Arizona, New Mexico, Utah, and Wyoming. U.S. Geological Survey Prof. Paper 2358.

Lloyd, D. S., J. P. Koenings, and J. D. La Perriere. 1987. Effects of turbidity in fresh waters of Alaska. North American Journal of Fisheries Management 7:18-33.

Lusby, G. C. 1970. Hydrologic and biotic effects of grazing versus non-grazing near Grand Junction, Colorado. Journal of Range Management 23:256-270.

McClelland, W. T., and M. A. Brusven. 1980. Effects of sedimentation on the behavior and distribution of riffle insects in a laboratory stream. Aquatic Insects 2(3): 161-169.

Mendelson, J. 1975. Feeding relationships among species of *Notropis* (Pisces: Cyprinidae) in a Wisconsin stream. Ecological Monographs 45:199-230.

Merritt, R. W., and K. W. Cummins. 1996. An introduction to the aquatic insects of North America. Third Edition, Kendall/Hunt. Dubuque, Iowa.

Meyer-Peter, E., and R. Müller. 1948. Formulas for bed load transport. Pages 39-64 *in* Proceedings of the 2nd Congress of the International Association for Hydraulic Research, Stockholm, 2: Paper No. 2.

Milhous, R. T., S. A. Hogan, S. R. Abt, and C. C. Watson. 1995. Sampling river-bed material: the barrel sampler. Rivers 5(4)239-249.

Milhous, R. T. 1998. Modeling of instream flow needs: the link between sediment and aquatic habitat. Regulated Rivers: Research & Management 14:79-94.

Mussetter, R. A., M. D. Harvey, L. W. Zevenbergen, and R. D. Tenney. 2001. A comparison of one- and two-dimensional hydrodynamic models for evaluating Colorado pikeminnow spawning habitat, Yampa River, Colorado. *In* D. J. Anthony, M. D. Harvey, J. B Laronne, M. P. Mosley, editors. Applying geomorphology to environmental management. Water Resources Publications, LLC:361-380.

Neill, C. R. 1968. Note on initial movement of coarse uniform bed material. Journal of Hydraulic Research. 6(2):173-176.

Newcombe, C. P., and D. D. MacDonald. 1991. Effects of suspended sediments on aquatic ecosystems. North American Journal of Fisheries Management 11:72-82.

Osmundson, D. B. et al. 1995. Relationships between flow and rare fish habitat in the 15-Mile Reach of the Upper Colorado River, Final Report. U.S. Fish and Wildlife Service, Grand Junction, Colorado.

Osmundson, D. B., and B. K. Scheer. 1998. Monitoring cobble-gravel embeddedness in the streambed of the Upper Colorado River, 1996-1997. Final Report, U.S. Fish and Wildlife Service. Grand Junction, Colorado.

Osmundson, D. B. 1999. Longitudinal variation in fish community structure and water temperature in the upper Colorado River: implications for Colorado pikeminnow habitat suitability. U.S. Fish and Wildlife Service. Grand Junction, Colorado.

Osmundson, D. B., R. J. Ryel, V. L. Lamarra, and J. Pitlick. 2002. Flow-sediment-biota relations: implications for river regulation effects on native fish abundance. Ecological Applications 12(6):1719-1739.

Parker, G., P. C. Klingeman, and D. G. McLean. 1982. Bed load and size distribution in paved gravel-bed streams. Journal of the Hydraulics Division, ASCE, 108(HY4):544-571.

Partheniades, E. 1965. Erosion and deposition in cohesive soils. Journal of Hydraulic Division ASCE:91:105-139.

Partheniades, E., and J. F. Kennedy. 1973. Depositional behavior of fine sediment in a turbulent fluid motion. Intl. Assoc. for Hydraulic Research, Chapter 41:1:707-729.

Patton, P. C., and Schumm, S. A. 1981. Ephemeral stream processes: implications for studies of quaternary valley fills. Quaternary Research 15:24-43.

Pitlick, J., and M. Van Steeter. 1994. Changes in morphology and endangered fish habitat of the Colorado River. Completion Report No. 188, Colorado Water Resources Institute, Colorado State University.

Pitlick, J, R. Cress, and M. M. Van Steeter. 1997. Geomorphic assessment of the potential for expanding the range of habitat used by native fishes in the Upper Colorado River.

Pitlick, J., and M. Van Steeter. 1998. Geomorphology and endangered fish habitats of the Upper Colorado River 2: linking sediment transport to habitat maintenance. Water Resources Research 34(2):303-316.

Pitlick, J., et al. 1999. Geomorphology and hydrology of the Colorado and Gunnison rivers and implication for habitats used by endangered fishes. Report for Recovery Implementation Program, Project No. 44-B. University of Colorado. Boulder, Colorado.

Pitlick, J., and R. Cress. 2000. Longitudinal trends in channel characteristics of the Colorado River and implications for food-web dynamics. Department of Geology, University of Colorado.

Pitlick, J., and P. Wilcock. 2001. Relations between streamflow, sediment transport, and aquatic habitat in regulated rivers. Geomorphic Process and Riverine Habitat, Water Science and Application 4:185-198.

Plafkin, J. L., M. T. Barbour, K. D. Porter, S. K. Gross, and R. M. Hughes. 1989. Rapid bioassessment protocols for use in streams and rivers: benthic macroinvertebrates and fish. EPA/444/4-89/001.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Pretegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime: a paradigm for river conservation and restoration. BioScience 47:769-784.

Poff, N. L., and J. V. Ward. 1989. Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. Canadian Journal of Fisheries and Aquatic Sciences 46:1805-1818.

Power, M. E. 2001. Controls on food webs in gravel-bedded rivers: the importance of the gravel-bed habitat to trophic dynamics. *In* M. P. Mosley, editor. Gravel-bed rivers. New Zealand Hydrological Society.

Resh, V. H., et al. 1988. The role of disturbance in stream ecology. Journal of North American Benthological Society 7:433-455.

Reynolds, J. B., and D. E. Simpson. 1978. Evaluation of fish sampling methods and rotenone census. Pages 11-24 *in* G. D. Novinger and J. G. Dillard, editors. New approaches to the management of small impoundments. North Central Division, American Fisheries Society, Special Publication 5.

Richards, K. 2001. Floods, channel dynamics, and riparian ecosystems. Pages 465-477 *in* M. P. Mosley, editor. Gravel Bed Rivers V. New Zealand Hydrological Society.

Rosenberg, D. M. and V. H. Resh. 1992. Introduction to freshwater biomonitoring and benthic invertebrates. Pages 1-9 *in* D. M. Rosenberg and V. H. Resh, editors. Freshwater Biomonitoring and Benthic Macroinvertebrates. Chapman and Hall, New York.

SAS Institute. 1996. SAS\STAT Software: changes and enhancements through release 6.11. SAS Institute Inc. Cary, North Carolina.

Schumm, S. A., and Hadley, R. F. 1957. Arroyos and the semi-arid cycle of erosion. American Journal of Science 255:161-174.

Schumm, S. A., M. D. Harvey, and C. C. Watson. 1984. Incised channels: morphology dynamics and control. Water Resources Publications. Littleton, Colorado.

Shields, A. 1936. Application of similarity principles and turbulence research to bed load movement. California Institute of Technology. Pasadena, California. Translation from German Original; Report 167.

Simons, D. B., and F. Sentürk. 1976. Sediment transport technology. Water Resources Publications.

Simons, D. B., and F. Sentürk. 1977. Sediment transport technology. Water Resources Publications.

Smerdon, E. T., and P. B. Beasley. 1961. Critical tractive forces in cohesive soils. Agricultural Engineering, January 1961.

Spahr, N. E., et al. 2000. Water quality in the Upper Colorado River Basin, Colorado, 1996-98. USGS Circular 1214: 1-33.

Stewart, G. B. 2001. Two-dimensional hydraulic modeling for making instream-flow recommendations. Master's Thesis. Colorado State University, Fort Collins, Colorado.

Sullivan, C. 1956. The importance of size grouping in population estimates employing electric shockers. Progressive Fish-Culturist 18:188-190.

Swift-Miller, S. M., B. M. Johnson, R. T. Muth, and D. Langlois. 1999. Distribution, abundance, and habitat use of Rio Grande sucker (*Catostomus plebeius*) in Hot Creek, Colorado. The Southwestern Naturalist 44(1):42-48.

Thompson, K. R. 1982. Characteristics of suspended-sediment in the San Juan River near Bluff, Utah. USGS Water Resources Investigation Report 82-4104.

Thompson, K. R. 1984. Annual suspended sediment loads in the Colorado River near Cisco, Utah. USGS Water Resources Investigation Report 85-4011.

Tyus, H. M. 1992. An instream flow philosophy for recovering endangered Colorado River fishes. Rivers 3(1):27-36.

U.S. Army Corps of Engineers. 1991. HEC-2, Water Surface Profiles, Version 4.6.0, Hydrologic Engineering Center. Davis, California.

U.S. Army Corps of Engineers. 1992. HEC-FFA, Flood frequency analysis, user's manual. Hydrologic Engineering Center. Davis, California.

U.S. Army Corps of Engineers. 1997. WES Users Guide to RMA2, Version 4.3.

Van Deventer, J. A., and W. S. Platts. 1989. Microcomputer software system for generating population statistics from electrofishing data – user's guide for MicroFish 3.0. General Technical Report Int-254. U.S. Department of Agriculture, Forest Service, Intermountain Research Station. Ogden, Utah.

Van Steeter, M., and J. Pitlick. 1998. Geomorphology and endangered fish habitats of the Upper Colorado River 1: historic changes in streamflow, sediment load, and channel morphology. Water Resources Research 34(2):287-302.

Ward, J. V., B. C. Kondratieff, and R .E. Zuellig. 2002. An illustrated guide to the mountain stream insects of Colorado. Second Edition. University Press of Colorado. Boulder, Colorado.

Waters, T. F. 1995. Sediment in streams: sources, biological effects, and control. American Fisheries Society Monograph 7.

Wells, S. G. 1988. Holocene and historic arroyo evolution in the Zuni River watershed, western New Mexico. Geol. Soc. Amer. Abstracts with Programs 21:A38.

Winner, R. W., B. W. Boesel, and M. P. Farrel. 1980. Insect community structure as an index of heavy-metal pollution in lotic ecosystems. Canadian Journal of Fisheries and Aquatic Sciences 37:647-655.

Wolman, M. G. 1954. A method of sampling coarse bed material. Transactions of the American Geophysical Union 35:951-956.

Wolman, M. G., and Miller, J. P. 1960. Magnitude and frequency of forces in geomorphic processes. Journal of Geology 68:54-74.

Wolman, M. G., and Gerson, R. 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surface Processes 3:189-208.

7 APPENDICES